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Abbreviations

ACAL	Alsace-Champagne-Ardenne-Lorraine
AFRA	Aircraft Fleet Recycling Association
ALPC	Aquitaine-Limousin-Poitou-Charentes
ANR	l’Agence Nationale de la Recherche
ARA	Auvergne-Rhône-Alpes
BAU	Business As Usual
BFC	Bourgogne-France-Comté
BMC	Bulk Moulding Compound
BMP	Best Management Practice
BRE	Bretagne
CEPCI	Chemical Engineering Plant Cost Index
CF	Carbon Fibre
CFRP	Carbon Fibre Reinforced Polymer
CVL	Centre-Val de Loire
D	Depreciation
EF	Ecological Footprint
EIA	Environmental Impact Assessment
EOL	End-of-Life
FENICS	FibErs recycling Network for Innovative Carbon composites by Solvolysis
FRP	Fibre Reinforced Polymer
FU	Functional unit
GAIA	Geometrical Analysis for Interactive Aid

GAMS	General Algebraic Modeling System
GF	Glass Fibre
GFRP	Glass Fibre Reinforced Polymer
GHG	Green House Gas
GIS	Geographic Information System
GLARE	Glass Laminate Aluminium Reinforced Epoxy
GWP	Global Warming Potential
GWPA	GWP impact of substituted products
GWPP	GWP impact of process
GWPTOT	GWP total of the system
HM	High tensile Modulus fibre type
HT	High Tenacity fibre type
IDF	Île-de France
IGN	Institut National de l'Information Géographique et Forestière
IM	Intermediate tensile Modulus fibre type
INV	Investment
ISM	Institute of Molecular Sciences
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LGC	Laboratoire de Génie Chimique
LM	Low tensile Modulus fibre type
LP	Linear Programming
LRMP	Languedoc-Roussillon-Midi-Pyrénées
MCDM	Multi-Criteria Decision Making
MFA	Material Flow Analysis
MILP	Mixed Integer Linear Programming

MINLP	Mixed Integer Non-Linear Programming
MRO	Maintenance, Repair and Overhaul
NLP	Non-Linear Programming
NOR	Normandie
NPCP	Nord Pas-de-Calais Picardie
NPV	Net Present Value
OC	Operation Cost per mass unit of waste
PACA	Provence-Alpes-Côte d'Azur
PAMELA	Process for Advanced Management of End-of-Life Aircraft
PAN	PolyAcryloNitrile
PE	PolyEthylene
PL	Pays de la Loire
PP	PolyPropylene
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PSE	Process Systems Engineering
PSI	Procédés et systèmes Industriels
PVC	PolyVinylChloride
QGIS	Quantum Geographic Information System
RTM	Resin Transfer Moulding
SCW	Supercritical Water
SEARRCH	Sustainability Engineering Assessment Research for Recycling Composite with High value
SMC	Sheet Moulding Compound
TBS	Toulouse Business School
TC	Total Annual Costs
TOPSIS	Technique for Order Preference by Similarly to Ideal Solution

TRL	Technology Readiness Level
UCF	Average Unit Cost per mass unit of recovered fibre
UCW	Average Unit Cost per mass unit of waste
UD	Unidirectional
UHM	Ultra High tensile Modulus fibre type
UN	United Nations
VAN	Valeur Actuelle Nette
VARTM	Vacuum Assisted Resin Transfer Moulding
VCF	Virgin Carbon Fibre
WEEE	Waste Electrical and Electronic Equipment

Abstract

Composites have been increasingly used in different applications in the last decade, especially in aerospace due to their high strength and lightweight characteristics. Indeed, the latest models of Airbus (A350) and Boeing (B787) have employed more than 50 wt% of composites, mainly Carbon Fibre Reinforced Polymers (CFRP). Yet, the increased use of CFRP has raised the environmental concerns about their end-of-life related to waste disposal, consumption of non-renewable resources for manufacturing and the need to recycle CFRP wastes. In this study, a generic model is developed in order to propose an optimal management of aerospace CFRP wastes taking into account economic and environmental objectives. Firstly, a life-cycle systemic approach is used to model the environmental impacts of CFRP recycling processes focusing on Global Warming Potential (GWP) following the guidelines of Life Cycle Assessment (LCA). The whole supply chain for recycling CFRP pathways is then modelled from aircraft dismantling sites to the reuse of recycled fibres in various applications. A multi-objective optimisation strategy based on mathematical programming, ε-constraint and lexicographic methods with appropriate decision-making techniques (M-TOPSIS, PROMETHEE-GAIA) has been developed to determine CFRP waste supply chain configurations. Various scenarios have been studied in order to take account the potential of existing recycling sites in a mono-period visions as well as the deployment of new sites in a multi-period approach considering the case study of France for illustration purpose. The solutions obtained from optimisation process allow developing optimal strategies for the implementation of CFRP recovery with recycled fibres (of acceptable quality) for the targeted substitution use while minimising cost /maximising profit for an economic criterion and minimising an environmental impact based on GWP.

Key words: multi-objective optimisation, recycling, composites materials, life cycle assessment waste management, sustainable development

Résumé

Depuis une dizaine d'années, les matériaux composites sont de plus en plus utilisés dans de nombreuses applications, et en particulier dans l'aéronautique grâce à leurs excellentes propriétés mécaniques et leur faible densité. Ainsi les derniers modèles d'Airbus (A350) et de Boeing (B787) utilisent plus de 50% en masse de composites, principalement des polymères renforcés de fibres de carbone (CFRP). Toutefois, l'augmentation de l'utilisation des CFRP soulève des préoccupations environnementales quant à leur fin de vie à travers l'élimination des déchets, la consommation de ressources non renouvelables ainsi que la nécessité de recycler les déchets CFRP. Dans ces travaux de thèse, un modèle générique est développé afin de proposer une gestion optimale des déchets de CFRP aéronautiques en prenant en compte simultanément des objectifs économiques et environnementaux. Ainsi, dans un premier temps une approche systémique suivant les lignes directrices d'une approche par Analyse de Cycle de Vie est effectuée afin de modéliser les impacts environnementaux des procédés de recyclage des CFRP, avec une attention toute particulière sur l'impact de réchauffement climatique. Ensuite, toute la chaîne logistique du recyclage des déchets CFRP est modélisée en partant des sites de démantèlement des avions jusqu'à la réutilisation des fibres recyclées vers d'autres applications possibles. Une stratégie d'optimisation multi-objectif de programmation mathématique, d'ε-contrainte et de technique lexicographique est développé mettent également en jeu des techniques d'aide à la décision appropriées (M-TOPSIS, PROMETHEE-GAIA). Différentes configurations de chaînes logistiques de déchet CFRP sont ainsi proposées et plusieurs scénarios sont étudiés et optimisés de façon à prendre en compte les sites de recyclage déjà existants dans une vision mono-période ainsi que déploiement de nouveaux sites selon une approche multi-période. Le cas de la France sert d'illustration à la démarche et les configurations proposées pour implanter de nouveaux sites de façon optimale traitant une fibre recyclée facilement valorisable pour des applications ciblées sont analysées et discutées minimisant le coût ou maximisant le profit pour un critère économique et minimisant un critère environnemental basé sur le potentiel de réchauffement climatique.

Mots-clés: optimisation multicritères, recyclage, matériaux composites, analyse cycle de vie, gestion de déchets, développement durable

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General Introduction

Carbon fibre composites have been increasingly used in different applications (aerospace, automotive, industries, recreation…) in the last decades due to their high strength and light weight characteristics. In aerospace, they have progressively replaced metals and alloys in order to reduce fuel consumption. Composites have been used originally in military aircraft and have then been adopted progressively in civil airplane from secondary part to primary structure in the latest models of Boeing and Airbus, e.g. B787 with 50 wt% in composite, A350 with 53 wt% in composite (Figure 1).

These two models have marked the revolution of CFRP composite utilisation in airframe with CFRP fuselage. Adopted since 1970s, CFRP is increasingly used in structural applications of aircraft to replace more conventional materials (steel, aluminium, alloys…) in order to design lighter products due to their low density and high performance of chemical and physical properties and become the major composite in recent models among the other composites (GFRP, GLARE, Carbon/Carbon Composite…). This material is constituted of two main components: carbon fibre and polymer matrix. In aerospace applications, carbon fibre exhibits the high mechanical properties and polymer matrix is principally thermoset.

In contrast to metal, glass, thermoplastics and many other engineering materials for which a solid recycling industry has been established, CFRP and composite materials in general have not yet been properly recycled and landfill still constitutes the main option used. The main difficulty of recycling is related to the heterogeneous nature of the matrix and the reinforcement, especially in the case of thermoset composite (Pickering, 2006). Various technologies have been developed for carbon fibre recovery from CFRP waste that are generally grouped into three categories, i.e., mechanical recycling, thermal recycling and chemical recycling. However, the lack of adequate markets, their current high recycling cost, and the lower quality of the recyclates are the major barriers for the commercialisation of recycled fibres.

Indeed, the aerospace sector has to face up with the problem of increasing CFRP waste. Regarding the long lifespan of airplane (20-30 years), the main stream of current CFRP waste may come from manufacturing of recent aircraft, which use high quantity of CFRP material. The flow of end-of-life CFRP waste from retired aircraft will be more important in the next decades when the high CFRP-content aircraft will be dismantled (Figure 2). In aviation, there is no legislation or regulation imposed on aircraft owners or aircraft manufacturers about how to design or deal an aircraft that meets proper and due end-of-life requirements like End-of-life Vehicle Directive and WEEE (Waste Electrical and Electronic Equipment) legislation in Europe (Van Heerden and Curran, 2011). However, recent programs of Boeing and Airbus like AFRA (Aircraft Fleet Recycling Association), PAMELA (Process for Advanced

Management of End-of-Life Aircraft) have motivated valorisation and reuse of reclaimed materials including CFRP and other composites in aviation:

- Aircraft Fleet Recycling Association (AFRA) was founded in 2006 with Boeing and different stakeholders throughout the supply chain, including aircraft/engine manufacturers, disassemblers and parts distributors, recyclers, leasing-finance, and research institution. Its objective is to improve industry performance and increase commercial value for end-of-life aircraft in terms of environmental and sustainable performance through Best Management Practice Guide (BMP) developed from the collective experience of AFRA's members, and the accreditation program.
- Besides, Airbus has conducted and participated in successive projects on life-cycle management. The case of A300 dismantling has been studied through the PAMELA project (Process for Advanced Management of End-of-Life Aircraft) initiated in 2005 that defined the optimum practices related to End-of-life aircraft phase in the frame of ISO 14001 with a valorisation rate up to 85wt% of plane components. FENICS (FibErs recycling Network for Innovative Carbon composites by Solvolysis), another project of Airbus launched in 2013, has worked specifically on solvolysis process and the post-recycling operations for recovery of carbon fibres from composites.

These initiatives focus largely on technical aspect of end-of-life aircraft dismantling and carbon fibre composite recycling process. Yet, to our knowledge, very few studies have been conducted on the modelling of waste management for composites wastes in general, namely for the aerospace sector: carbon fibre recovery can be viewed as a complex problem due to the nature of the involved processes (some of them have not reached an advanced maturity level), to waste types and recovered fibre markets, etc. It must be yet emphasized that waste management models and their applications to sustainable system have been mainly developed and applied for municipal cases.

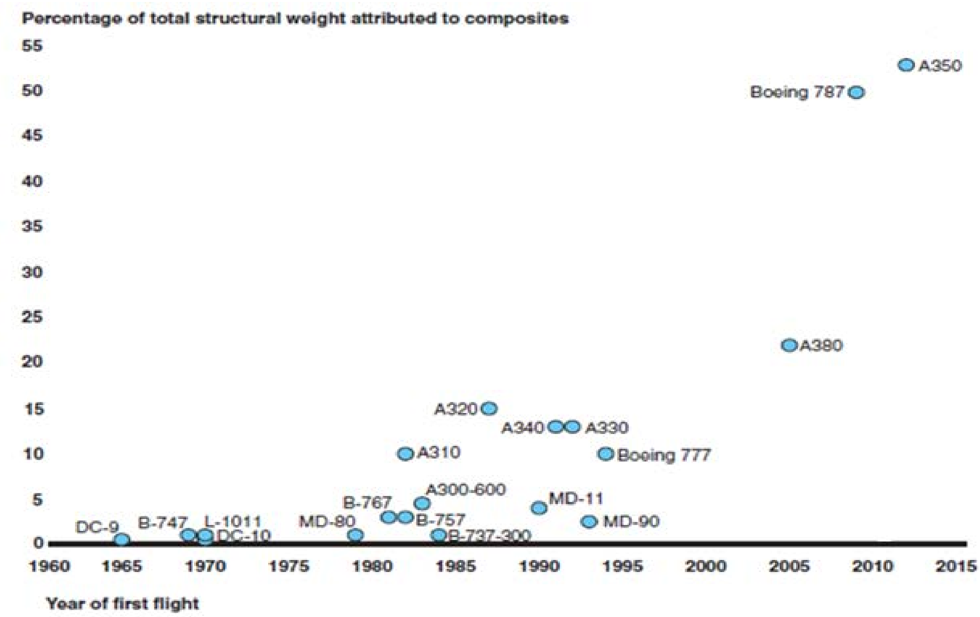

Figure1: Weight Percentage of Composites in Airplane Models over Time (GAO, 2011)

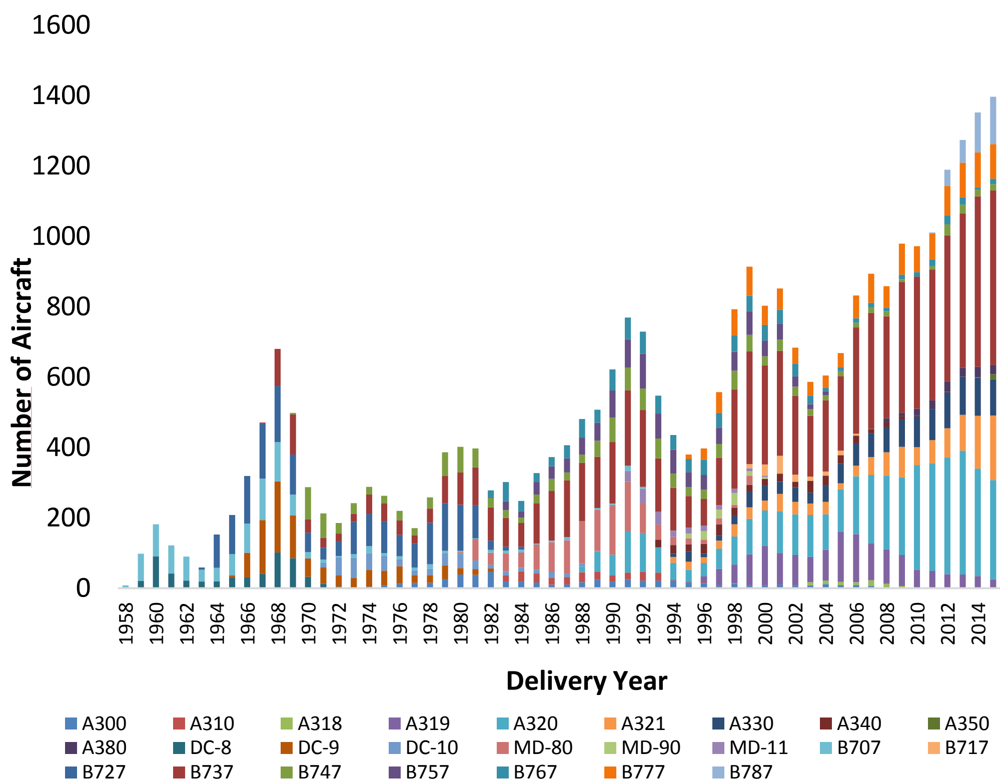

Figure 2: Number of Yearly Delivered Airbus-Boeing Aircraft per Model 1958-2015 (based on reports of Airbus and Boeing)

In this context, the SEARRCH project (ANR-13-ECOT-0005), which stands for Sustainability Engineering Assessment Research for Recycling Composite with High value, coordinated by Altran Research has been initiated in 2013 under the label of Aerospace Valley global competitive cluster and the financial support of the "Agence Nationale de la Recherche" (ANR). SEARRCH is a pre-normative research project on sustainability. Its objective is to design the innovative assets (knowledge, models, methods, tools…) in order to evaluate environmental, economic and social performance of composite recycling industries. The studied system of aerospace CFRP waste management in SEARRCH is developed from the life cycle of CFRP (see Figure 3).

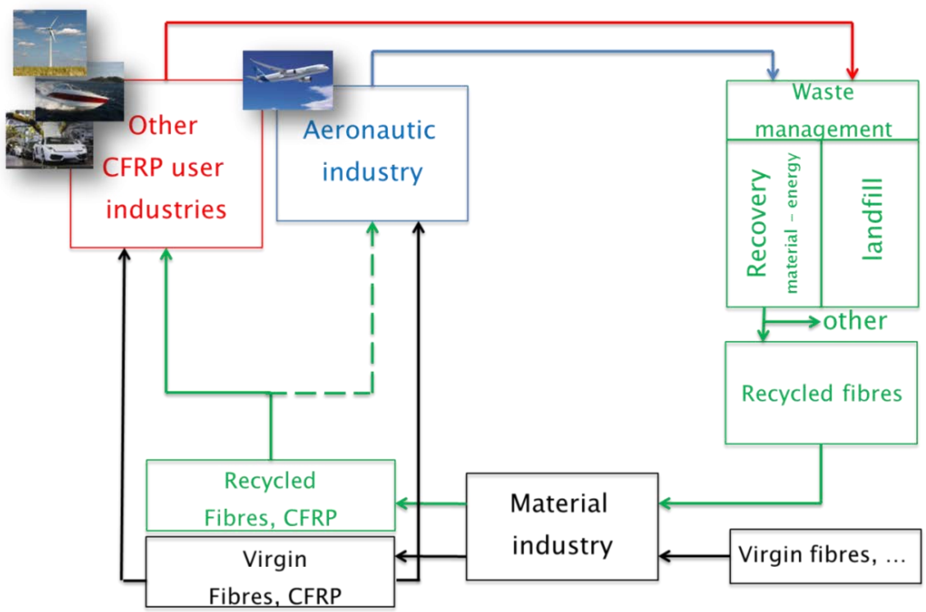

Figure 3: Simplified life cycle of CFRP (from SEARRCH project)

Among the objectives of the SEARRCH project, some of them must be highlighted:

1. The definition of Key Sustainability Performance Indicators for assessment of the composite recycling industry based on the three pillars of sustainability (environment, society, economy);

2. The development of models and methods for studying recycling options;

3. The development of a multi-criteria optimisation framework taking into account environmental and economic criteria of the CFRP supply chain for deployment purpose;

4. The development of an economic model for market development;

5. The development of generalised framework for composite recycling.

To achieve the goal, SEARRCH is composed by a multidisciplinary consortium of four partners (Figure 4), i.e. Altran Research (coordinator), ISM (Institute of Molecular Sciences), LGC (Laboratoire de Génie Chimique), and TBS (Toulouse Business School) that are experts in engineering, process modelling, recycling systems, Life Cycle Assessment (LCA), material flow accounting, applied mathematics, multi-objective optimisation, decision-making tools, environmental economy, environmental regulation and sustainable business.

Figure 4: Members in SEARRCH project (SEARRCH-International Conference Green Aviation, November 7, 2014 – Le Bourget)

This PhD project is part and parcel of SEARRCH and was conducted from February 2014 to Mars 2017 at the Laboratory of Chemical Engineering (LGC), UMR CNRS 5503 (University of Toulouse, INPT UPS) in the Process Systems Engineering (PSE) department. This study focuses on the development of a methodological framework for the design of aerospace CFRP waste management.

This manuscript is organised into six chapters.

Chapter 1 *Motivation for the study:* this chapter is dedicated to the issue of aerospace CFRP waste management including the presentation of composite materials, in particular CFRP manufacturing, the state of art in carbon fibre recycling techniques and the review on waste management modelling.

Chapter 2 *Methods and Tools*: the methodologies and the numerical tools used throughout this work for system modelling, optimisation and decision-making are presented to provide the reader the required level of information to tackle the following chapters.

Chapter 3 *Economic and Environmental Assessment of Waste Treatment Pathways for CFRP:* a global review of available techniques in CFRP waste management is proposed with the assessment of each pathway through its inputs and outputs under economic and environmental indicators.

Chapter 4 *A bi-criteria optimisation* strategy involving a Linear Programming (LP) formulation is developed for aerospace CFRP waste management following *a mono-period approach*. The system that is considered for aerospace CFRP waste management including the network, the waste types, the compatibility between wastes and techniques is presented in detail.

Chapter 5 The extension to *a dynamic bi-criteria optimisation for aerospace CFRP waste management* is than proposed in a *multi-period vision* by use of Mixed Integer Linear Programming (MILP). A sensibility study on the evolution of waste quantity considering different scenarios is then conducted.

Chapter 6 Conclusions and Perspectives

Introduction Générale

Depuis une quinzaine d'années, les composites en fibres de carbone sont de plus en plus utilisés dans différentes applications (aéronautique, automobile, industries, loisirs ...) en raison de leur grande résistance et de leur légèreté. Dans l'industrie aéronautique, ils ont progressivement remplacé les métaux et les alliages en raison de leur légèreté et leur rigidité afin de réduire la consommation de carburant et par conséquent l'impact environnemental du secteur de l'aviation. Les composites ont été utilisés à initialement dans des avions militaires et ont été ensuite progressivement adoptés dans des structures secondaires jusqu'aux parties primaires dans les avions de ligne (Figure 1).

Les derniers modèles de Boeing et Airbus, B787 avec 50% et A350 avec 53% en masse du composite ont marqué le fort développement de l'utilisation du composite CFRP dans les applications aéronautiques avec un fuselage en CFRP. Depuis 1970, le composite CFRP est de plus en plus utilisé dans les parties structurelles des avions pour remplacer des matériaux conventionnels (acier, aluminium, alliages ...) afin de concevoir des pièces plus légers avec leur faible densité et leurs propriétés chimiques et physiques élevées. CFRP est devenu le composite principal dans les modèles d'avion récents parmi les autres composites (GFRP, GLARE, Carbone / Carbone Composite ...). Ce matériau est constitué de deux composants principaux: la fibre de carbone et la matrice polymère. Dans les applications aéronautiques, la fibre de carbone présente des propriétés mécaniques excellentes et la matrice polymère est principalement de type thermodurcissable.

Au contraire du métal, du verre, des thermoplastiques et des autres nombreux matériaux d'ingénierie pour lesquels l'industrie du recyclage a été bien établie, le CFRP et les matériaux composites en général n'ont pas encore été une filière de recyclage établie et l'enfouissement constitue toujours la principale option utilisée. La principale difficulté du recyclage est liée à sa nature hétérogène matrice-fibre, en particulier dans le cas du composite thermodurcissable (Pickering, 2006). Diverses technologies ont été développées pour le recyclage de fibres de carbone à partir de déchets de CFRP généralement regroupées en trois catégories, i.e., mécanique, thermique et chimique. Cependant, le manque de marchés adéquats, le coût actuel de recyclage élevé et la qualité dégradée des produits recyclés sont les principaux obstacles à la commercialisation des fibres recyclées.

Or, le secteur aéronautique sera confronté dans les années à venir à la problématique de l'augmentation croissante des déchets de CFRP liés à son activité. Compte tenu de la durée de vie moyenne d'un avion (20-30 ans), le principal flux des déchets CFRP proviendra du CFRP issu de la fabricationde l'avion et compte tenu des évolutions de fabrication, la génération des déchets CFRP en fin de vie des avions sera plus importante dans les prochaines décennies lorsque les avions à forte teneur en CFRP seront démantelés (Figure 2). Dans le secteur aéronautique, il n'existe pas encore de législation ou de réglementation imposant aux propriétaires d'avions ou aux fabricants une responsabilité élargie vis-àvis du recyclage des avions telle que la directive sur les véhicules en fin de vie et les déchets d'équipements électriques et électroniques en Europe (Van Heerden and Curran, 2011). Cependant, les programmes récents de Boeing et d'Airbus comme AFRA (Aircraft Fleet Recycling Association), et PAMELA (Process for Advanced Management of End-of-Life Aircraft) ont encouragé la valorisation et la réutilisation des matériaux recyclés, y compris le CFRP ainsi que d'autres composites dans le secteur aéronautique :

- L'association "Aircraft Fleet Recycling Association" (AFRA) a été fondée en 2006 par Boeing et différentes parties prenantes de toute la chaîne d'approvisionnement (constructeurs d'avions / moteurs, fournisseurs de pièces, recycleurs, institutions de recherche…). Son objectif est d'améliorer l'efficacité de l'industrie et d'accroître la valeur commerciale des avions en termes de performances environnementales en satisfaisant les lignes directrices du guide "Best Management Practice" (BMP), qui est élaboré à partir de l'expérience collective des membres de l'AFRA, et de leur programme d'accréditation.
- Airbus a également mené et participé à des projets successifs sur la gestion du cycle de vie des avions. Pour cas d'étude sur le démantèlement de l'A300, le projet PAMELA (Process for Advanced Management of End-of-Life Aircraft) initié en 2005, a défini des pratiques pour le traitement des avions fin de vie dans le cadre de la norme l'ISO 14001. Un taux de valorisation jusqu'à 85 % en masse d'avion pu être établi. Un autre projet d'Airbus, FENICS (FibErs recycling Network for Innovative Carbon composites by Solvolysis), lancé en 2013, a travaillé sur spécifiquement le procédé de solvolyse et les opérations de post-recyclage pour la récupération des fibres de carbone dans les déchets de composites.
- Peut également être mentionné à ce niveau l'entreprise Tarmac Aerosave (Azereix, Hautes Pyrénées) qui associe dans son capital Airbus, suez Environnement et le groupe safran, à proximité de la plateforme aéroportuaire de Tarbes-Lourdes-Pyrénées, spécialisé notamment dans le démantèlement d'avions en fin de vie.

Ces initiatives portent principalement sur les aspects techniques du démantèlement des avions en fin de vie ainsi que sur des procédés spécifiques de recyclage des fibres de carbone. Cependant, à notre connaissance, très peu d'études ont été menés sur la modélisation de la gestion des déchets de composites en générale ou dans le secteur aéronautique En plus, le recyclage des fibres de carbone est un problème complexe lié au type de procédés, au type de déchets, au marché des fibres recyclées… Actuellement, à notre connaissance, la majorité des modèles de gestion de déchets de leurs applications concernant les déchets municipaux.

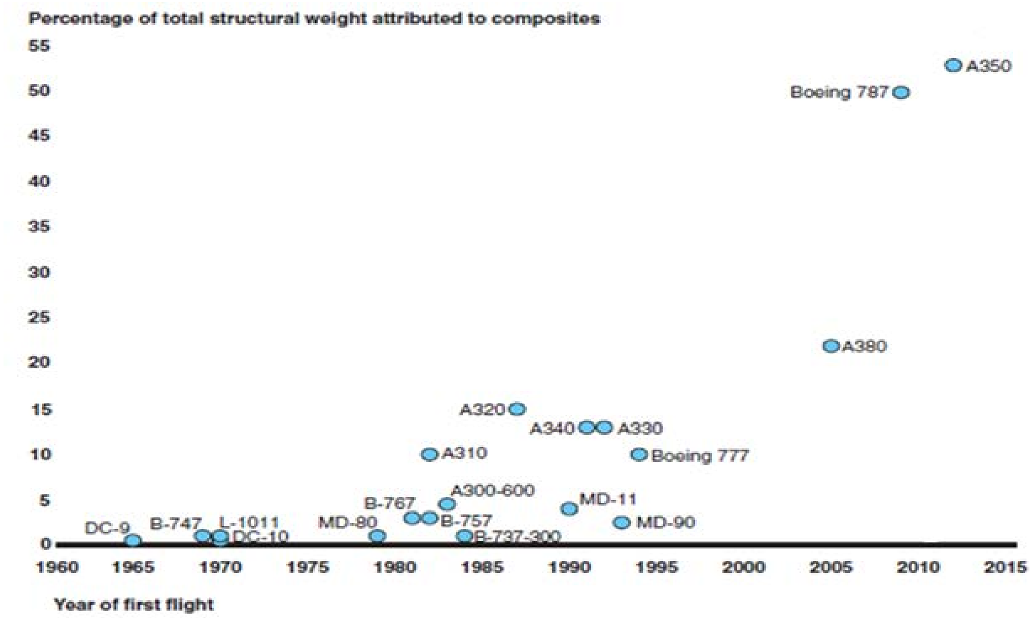

Figure 1: Proportion en masse des composites dans les modèles d'avions de ligne depuis 1965 (GAO, 2011)

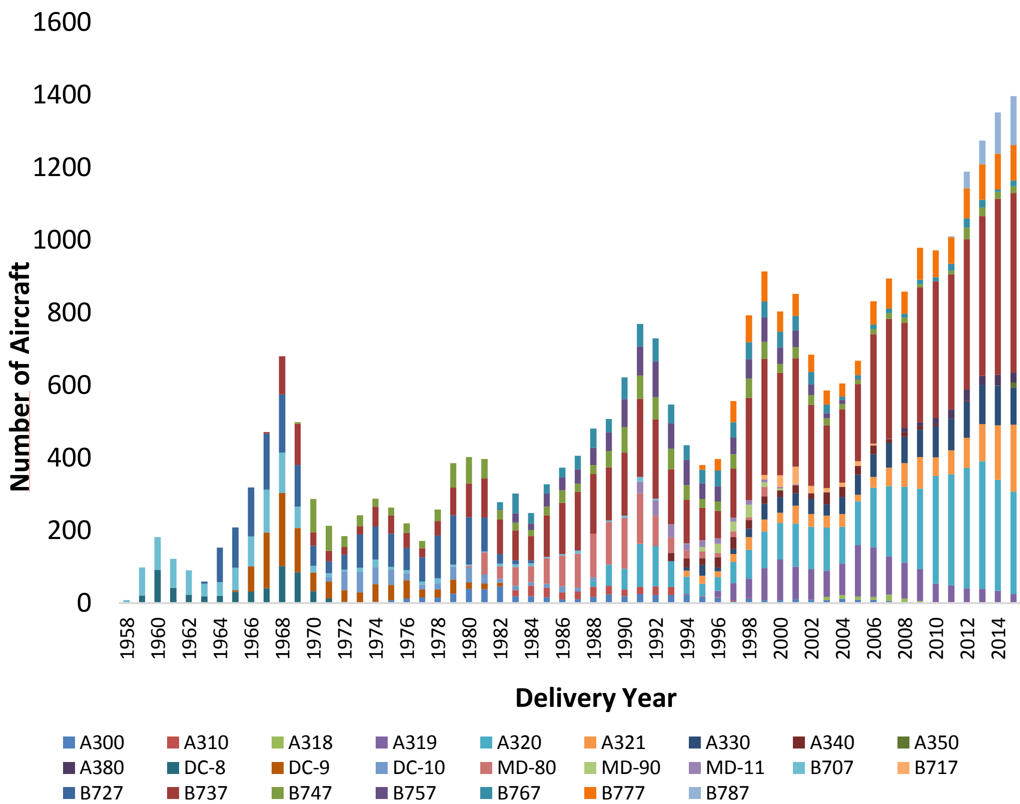

Figure 2: Nombre d'avions Airbus-Boeing livrés par an de 1958 à 2015 (basé sur Airbus et Boeing)

Dans ce contexte, le projet SEARRCH (ANR-13-ECOT-0005), acronyme de Sustainability Engineering Assessment Research for Recycling Composite with High value, labellisé par Aerospace Valley et financé par l'Agence Nationale de la Recherche (ANR) de 2014 à 2017, vise à concevoir un système d'évaluation permettant d'apprécier les performances environnementales, économiques et sociales des filières de recyclage des matériaux composites, plus particulièrement en vue de la gestion des déchets de CFRP aéronautique. Le système étudié pour la gestion des déchets de CFRP aéronautiques dans le projet SEARRCH est développé en prenant compte le cycle de vie de ce matériau (Figure 3).

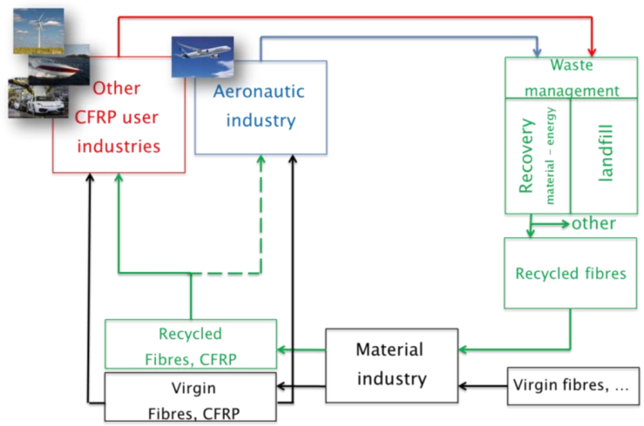

Figure 3: Le cycle de vie simplifié de CFRP (du projet SEARRCH)

Le projet SEARRCH rassemble un consortium pluridisciplinaire regroupant quatre partenaires (Figure 4): Altran Research (coordinateur), ISM (Institut des Sciences Moléculaires), LGC (Laboratoire de Génie Chimique) et TBS (Toulouse Business School) avec des compétences complémentaires en ingénierie, sciences de l'environnement/analyse du cycle de vie, génie des procédés, mathématiques appliquées et économie.

Figure 4: Les partenaires du projet (SEARRCH-International Conference Green Aviation, 7 Novembre, 2014 – Le Bourget)

Cinq points importants visés dans le projet SEARRCH :

1. L'élaboration d'une liste d'indicateurs clés du développement durable pour l'évaluation de l'industrie du recyclage des composites selon les trois piliers du développement durable : environnement, société et économie ;

2. Le développement de méthodes d'étude des options de recyclage et leurs indicateurs associés

3. Le développement de méthodes et outils d'étude pour concevoir une chaîne logisitque de recyclage du déchet CFRP aéronautique et ses indicateurs associés ;

4. L'élaboration de modèles économiques face à l'introduction de normes et d'initiatives économiques pour construire un système durable ;

5. La définition d'une structure générique pour le recyclage des matériaux composites.

Ce travail de thèse a été réalisé de Février 2014 à Mars 2017 au Laboratoire de Génie Chimique (LGC), UMR CNRS 5503 (Université de Toulouse, INPT UPS) dans le département Procédés et systèmes Industriels (PSI).

La thèse est organisée en six chapitres dont le contenu est brièvement présenté ci-après.

Chapitre 1 *Motivation de l'étude:* ce chapitre présente le contexte de la gestion des déchets CFRP aéronautique, y compris la présentation des matériaux composites et de la fabrication de CFRP, ainsi que l'état de l'art des techniques de recyclage des fibres de carbone. Il recense également les études portant sur la modélisation de la gestion des déchets.

Chapitre 2 *Méthodes et outils:* la description des méthodes et outils numériques utilisés pour la modélisation et l'optimisation dans cette étude fait l'objet de ce chapitre.

Chapitre 3 *Évaluation économique et environnementale* des voies de traitement des déchets de CFRP : une revue générale des techniques disponibles pour la gestion des déchets de CFRP est ainsi proposée. Chacune des voies est ensuite analysée et discuté en vue de son évaluation à partir de la connaissance d'intrants, produits et émissions selon des indicateurs économiques et environnementaux.

Chapitre 4 Une *optimisation bi-critères* pour la gestion des déchets CFRP aéronautique est développée selon une approche *mono-période* en mettant en jeu une formulation par programmation linéaire (Linear Programming - LP). Le système étudié pour la gestion des déchets CFRP aéronautique est présenté en faisant intervenir les types de déchets ainsi que la compatibilité entre déchets et techniques notamment.

Chapitre 5 Une *optimisation bi-critères* pour la gestion des déchets CFRP aéronautique avec une approche *multi-période* par programmation linéaire mixte en nombres entiers (Mixed Integer Linear Programming – MILP) est ensuite développée. L'extension du système au cas multi-période est étudiée à travers une analyse de sensibilité portant sur l'évolution temporelle de la quantité de déchets selon différents scénarii.

Chapitre 6 *Conclusions et perspectives*

Scientific Communications

1. Phuong Anh VO DONG[a], Catherine AZZARO-PANTEL[a], Marianne BOIX[a], Leslie JACQUEMIN[b], Anne-Laure CADÈNE[b], Serge DOMENECH[a], Assessment of potential benefits from different pathways of fibre reinforced thermoset composite waste, Recycling 15 Conference, Mars 2015, Metz (France) - Presentation
2. Phuong Anh VO DONG[a], Catherine AZZARO-PANTEL[a], Marianne BOIX[a], Leslie JACQUEMIN[b], Serge DOMENECH[a], Modelling of environmental impacts and economic benefits of fibre reinforced polymers composite recycling pathways, European Symposium on Computer-Aided Process Engineering (ESCAPE) 25, June 2015, Copenhagen (Denmark) - Poster and Proceeding
3. Phuong Anh VO DONG[a], Catherine AZZARO-PANTEL[a], Marianne BOIX[a], Leslie JACQUEMIN[b], Anne-Laure CADÈNE[b], Serge DOMENECH[a], A Bi-criteria optimisation approach for aerospace carbon fibre reinforced polymer waste management in France, Wasteeng 2016, May 2016, Albi (France) - Presentation
4. Phuong Anh VO DONG[a], Catherine AZZARO-PANTEL[a], Marianne BOIX[a], Leslie JACQUEMIN[b], Anne-Laure CADÈNE[b], A Bicriteria Optimisation Approach for Waste Management of Carbon Fibre Reinforced Polymers Used in Aerospace Applications: Application to the Case Study of France, Waste and Biomass Valorization, 1-22, 2016.

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CHAPTER 1

Motivation for the Study

Abstract

The importance of developing sustainable system for aerospace CFRP waste management is highlighted in this chapter. It also presents the background of the aerospace CFRP industry and the state-of-art of FRP/CFRP recycling techniques. The motivations for the study thus can be justified from economic and environmental viewpoints. The production of virgin carbon fibre and CFRP requires a huge amount of fossil energy leading to high GHG emissions. The reuse of recycled carbon fibres could thus substitute a part of virgin carbon fibres to face with an increased demand. Although it is hard to separate fibres/carbon fibres from the heterogeneous structure of FRP/CFRP composites, the recent breakthrough on FRP/CFRP composites recycling techniques has improved the recovery yield of fibres/carbon fibres from composite and quality of recovered fibres. The current studies on composite wastes have only been focused on the comparison of FRP/CFRP waste treatment pathways, without encompassing a holistic approach. Yet, modelling and optimisation of the entire system play are essential to tackle the global issue of CFRP waste management, the dynamic waste evolution, the pathways for fibre recovery as well as the potential markets for recycled carbon fibre. This chapter presents the situation of composites materials/CFRP industry, their applications in aerospace sector, recycling techniques and the framework of waste management. These concepts will be applied for modelling the system of CFRP waste management in optimisation. The scientific objective and motivation of the study will conclude this chapter.

Résumé

Le développement d'un système durable pour la gestion des déchets de CFRP aéronautique constitue un point clé dont l'importance est soulignée dans ce chapitre. Ce chapitre présente le contexte de l'industrie de CFRP aéronautique et l'état de l'art des techniques de recyclage des FRP/CFRP. La production de fibre de carbone vierge et de CFRP est très énergivore conduisant à des émissions importantes de gaz à effet de serre. La réutilisation des fibres de carbone recyclées pourrait ainsi remplacer une partie des fibres de carbone vierges dont la demande est croissante. Bien qu'il soit difficile de séparer les fibres/fibres de carbone à partir de structures hétérogènes de FRP/CFRP composites, les progrès actuels des techniques de recyclage des composites FRP/CFRP ont permis d'améliorer le rendement de recyclage des fibres/fibres de carbone du composite et la qualité des fibres recyclées. Les travaux actuels sur les techniques de recyclage se sont essentiellement concentrés sur la comparaison des voies de traitement des déchets FRP/CFRP, sans prendre en compte une vision holistique. Cependant, la modélisation et l'optimisation de l'ensemble du système sont essentielles pour aborder d'un point de vue global de problème de gestion des déchets de CFRP en prenant en compte l'évolution des déchets, les différentes stratégies de valorisation possibles et les marchés de la fibre de carbone recyclée. Un revue de l'industrie des matériaux composites/CFRP, de leurs applications dans le secteur aéronautique, des techniques de recyclage et des modèles de gestion des déchets est détaillé dans ce chapitre. Ces concepts seront appliqués pour la modélisation du système de gestion des déchets CFRP et son optimisation. L'objectif scientifique et la motivation de l'étude concluront ce chapitre.

1.1. Introduction

Consumerism lifestyle has pushed mass industrialisation and accumulated an incredible volume of resources. The depletion of resource is therefore in extremely urgent status to meet the increasing demand of consumption. According to (Global Footprint Network, 2016), today it takes the equivalent of 1.6 planets Earth to provide the resources we use and absorb our waste. United Nations (UN) also predict the need of two Earths by the 2030s if current population and consumption trends continue (Figure 1-1). This situation has also made the access to materials a critical issue of national security of many nations. The increasing amount of waste is also another consequence of this phenomenon. Most of wastes generally have to go into landfill or incineration for disposal because of economic reasons. These solutions however have negative impacts on environment.

Consumption can be defined traditionally at the end of economic activities from extraction of resources to production of goods/services and their distribution among people and groups; and the goods and services themselves come to be used goods (Goodwin et al., 2013). However, in the new concept, consumption can create the resource base for the next round of economy activity and go to the circular economy framework on using recycling activities. Recycling now plays an important role in waste management on reducing waste disposal and improving the resource efficiency. In economic view, this alternative depends largely on the cost of conventional production from primary resources and the waste disposal fees. Since the industrial revolution, the low-cost mass production techniques reduced the costs of materials and products; it also reduced the interest on recycling. For high technology recycling, it is hard to be chosen as solution among cheaper disposal options without legislation barrier.

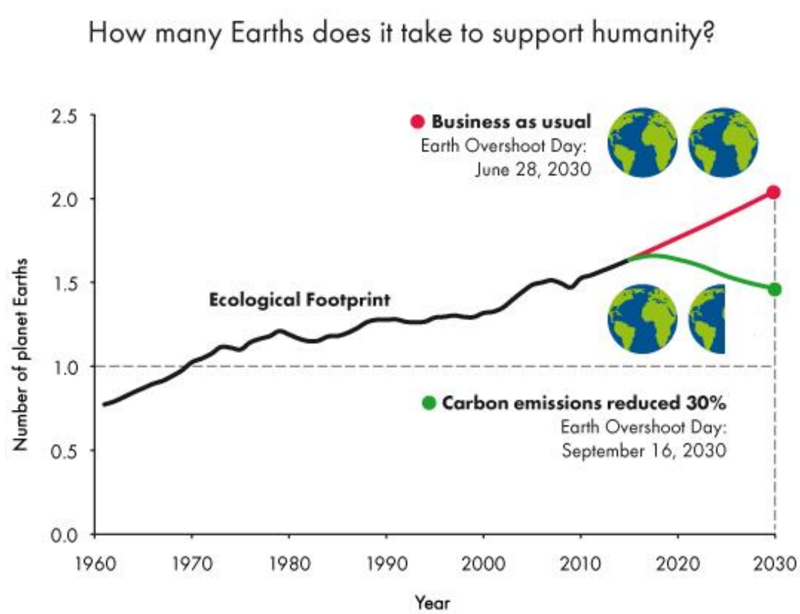


Figure 1-1: Evolution of World Footprint 1960-2030 (*estimation) (Global Footprint Network, 2016)*

Since its invention by Edison over 100 years ago (Edison, 1880), carbon fibre (CF) has been used in numerous applications (Figure 1-2), such as aerospace, automotive, sports... Due to its lightness, and good mechanical properties, CF is excellent reinforcement fibre in composite. Moreover, with the good corrosion resistance, carbon fibre composites (CFC) have substituted increasingly conventional materials (e.g. steel, aluminium alloys). In transport applications, the use of CFC has double effects: weight reduction of vehicles (e.g. aircraft, car) and reduction of fuel consumption as consequence. The recent aircraft models of Boeing (B787) and Airbus (A350) have high content of CFC with more than 50 % in this material. The market of Carbon Fibre Reinforced Polymers (CFRP), the main CFC, will need 175 000 tonnes/year with the annual growth rate of 11 % in 2021 (Witten et al., 2015).

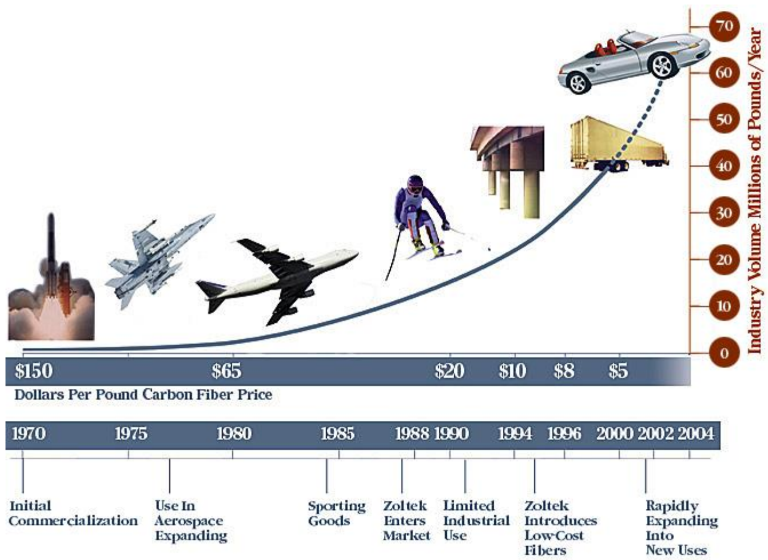


Figure 1-2: Carbon fibre uses history (www.utsi.edu)

While the use of CFRP provides many advantages, these materials also present some challenges for environment. The growing volume of CFRP in applications today will lead to larger quantity of CFRP waste generated tomorrow. The production of CF consumes high energy and releases hazardous gas (Suzuki and Takahashi, 2005; Grzanka, 2014). Otherwise, the global demand of carbon fibre is expected to exceed production capacity in 2015 if growth remains at this rate. In that context, the interest of recycling is threefold: first, it is necessary to limit the accumulation of waste that is likely to be generated; second, recycling could be a fibre supply solution in order to meet future demand (Black, 2012) and third, recycling could be expected as a less-energy-intensive operation with lower environmental impact than the traditional way to produce CFRP, bypassing some operation steps.

Due to the complexity in concept and composition, CFRP scraps cannot be easily recycled like metals or plastics materials. The lack of solid markets for recycled carbon fibre is another reason why most of CFRP wastes are currently landfilled or incinerated (Yang et al., 2012). At present, there are no legislations which are specific for composite wastes in general. However, they can be concerned by the regulations applied on the components in composite (e.g. organic substances, hazardous additives) like the European Directive on Landfill of Waste (Directive 1999/31/EC, 1999) or the applications generating waste streams like the End-of-life Vehicle Directive (Directive 2000/53/EC, 2000).

Facing with the increasing volume of CFRP waste, the waste management of these materials is poorly prepared on both techniques and legislations. The current solutions with landfill and incineration will be no longer the best choices in future regarding the ban of landfill and the restriction of waste incineration in several countries. Otherwise, these techniques lead to the loss of recoverable products in CFRP wastes such as recycled carbon fibre which can be reinserted to highly-demanded CF markets. CFRP recycling techniques have had important progressions on operation process and quality of recycled products. For Fibre Reinforced Polymer Composites in general, although only grinding and pyrolysis are industrialised, a wide range of recycling techniques are on development (Oliveux et al., 2015a) with different conditions and multiple products. The advancement of recycling techniques helps widening the portfolio of options for CFRP waste treatment.

In this context, the objective of this research project is to study the CFRP waste management with a set of treatment options. The economic and environmental assessments tools are used to design the relevant networks in order to take into account both economic and environmental advantages and drawbacks between waste treatment options. With these criteria, the optimisation process will be carried out in waste management model. Besides, the markets or recovered products will be integrated in waste management.

In this introduction chapter, the next section is dedicated to the general presentation of composites materials including the main types, their concepts and the principal components, especially Carbon Fibre reinforced Polymer type. Its components and fabrication process will be briefly presented in order to identify the waste types that will be tackled in the studied system and the potential benefit of recycling over conventional production. The state of the art of CFRP recycling techniques is the core of the section 1.3. Section 1.4 will present a review on the models and the methods for modelling waste management. These concepts will be applied for modelling the system of CFRP waste management and its optimisation. The scientific objective and motivation of the study in section 1.5 will conclude this chapter.

1.2. Composites Materials

1.2.1. Classifications of Composites Materials

A composite can be considered as unification made up of two or more different elements. Similarly, a composite material is a material that is composed of at least two materials of different nature (phase, properties…). The choice of the type and the arrangement of the constituents lead to a composite material which combines the best properties of each material component. Composite materials can be found in numerous applications, for examples, earth plaster, concrete, fibre reinforced polymers, etc.

A composite material consists of one or more discontinuous phases distributed in a continuous phase. The discontinuous phase, which is usually harder in mechanical properties than those of the continuous phase, is used as reinforcement. The continuous phase is called matrix. The properties of composite materials depend principally on the nature of the components and their properties, their geometric distribution and the interface of reinforcement/matrix. Composite materials can be classified by the nature of matrix: organic, metal, and mineral. Based on the geometric concept, there are two main types of composite materials: laminate, and sandwich. Table 1-1 shows the main types of composite materials and their applications based on these classifications.

Table 1-1: Composite materials and their applications (Berthelot, 2012)

Type of composite	Examples		
	Products	Components	Applications
Composite of organic matrix	Paper cardboard	Resin, fillers, cellulose fibres	Printing, packaging…
	Laminate	Resin, fillers, carbon/glass/Kevlar… fibres	Recreation automotive, aerospace
Composite of mineral matrix	Concrete	Cement, sand, aggregates	Construction
	Ceramic composite	Ceramic, ceramic fibres	Thermo-mechanic parts
Composite of metal matrix		Aluminium, bore/carbon fibre	Aerospace
Sandwiches	Honeycomb	Skin (laminate)/core	Recreation, aerospace

For the shape of reinforcement, the fibre-reinforced composite is separated from the particle-reinforced composite due to the mechanical application.

In fibre-reinforced composites, the fibres are utilised either in the form of the continuous fibres or in the form of staple fibres (chopped fibres). With fibre's anisotropic property, the mechanical properties of composite can be modified and modulated by working on the arrangement of the fibres, their orientation and the proportion of the components. The fibre-reinforced composites are used in products which require high mechanical resistance.

In particle-reinforced composites, the reinforcement is in the form of particle. The length-to-width ratio of the particles is close to unity. A particle, as opposed to fibre, does not have any preferred dimensions. The particles are used generally to improve certain properties of the materials or matrix such as rigidity, heat resistance, resistance to abrasion, reduced shrinkage, etc. In many cases, the particles are used simply to reduce the material cost without impact on characteristics of material.

Carbon Fibre Reinforced Polymer (CFRP), the subject of this study, is a polymeric (organic) matrix composite reinforced by carbon fibre. In function of the applications, CFRP can be used in laminate form only or incorporated with a core component to form a sandwich structure. The following part of this section will describe the principle of CFRP fabrication.

1.2.2. Carbone fibre production

Carbon fibre filament was produced at first by Edison during his work on incandescent light bulbs more than 100 years ago. These fibres were prepared by carbonisation of bamboo fibres later from regenerated cellulose (Edison, 1880). In the late 1950s carbon fibres were elaborated in a similar way from synthetic rayon for high temperature missile applications (Tang and Bacon, 1964). The technical and commercial breakthrough for high performance carbon fibres started in the late 1960s after introduction of the PAN (PolyAcryloNitrile) process by Japanese. The carbon yield for PAN is 50% whereas rayon carbonisation provides less than 30% carbon only. PAN based fibres also had superior physical properties compared to rayon based fibres. Heritage from textile industry, the PAN process turned out to be more economical due to the less expensive precursor polymer (PAN) and to a simpler fabrication process and become actual standard process (Fitzer, 1989). Carbon fibres were also prepared from pitch fibre precursor. The properties of pitch based carbon fibres are generally inferior to PAN based carbon fibres because of its isotropic property. The anisotropic pitch carbon fibre with high mechanical properties can be produced but the process is expensive.

In the beginning, the carbon fibre fabrication generally started with the availability of suitable precursors, there was no development of special precursor. Nowadays, there have been numerous studies on different precursors for carbon fibres, such as polyethylene, lignin to reduce precursor cost. However, much more efforts are necessary to improve their carbon fibre properties and processes compared to the three large-scale precursors of carbon fibres which are PAN, rayon and pitches (Chand, 2000; Frank et al., 2012). PAN-carbon fibres actually dominate the global market with 90%, the remaining 10% are made from rayon or pitch (Zoltek, 2016).

Carbon fibres do not suffer from stress corrosion or stress rupture failures at room temperatures like glass and organic polymeric fibres. Even at high temperature, mechanical properties of carbon fibre are outstanding compared to other material (Dostal, 1987). Therefore, carbon fibres composites are employed to applications where strength, stiffness, lower weight and excellent fatigue strength are critical requirements in normal or severe conditions (Dostal, 1987). The excellent properties of carbon fibre come from their molecular structure, a nearly perfect graphite structure. In carbon fibre production, the consecutive thermal operations (oxidation, carbonisation and graphitisation, see Figure 1-3) transform precursor with the poorly ordered structure to carbon fibre with a more ordered form. In function of the operational conditions, various mechanical-based ranges of carbon fibre are produced which are used in distinguished applications (Figure 1-4). Some physical properties of high tensile modulus (HM) carbon fibre and other fibre (E-glass fibre and Kevlar fibre) can be found in Table 1-2. Due to their excellent mechanical properties, carbon fibres are used mostly as reinforcement in advanced composites.

However, the energy needed for the processing of ex-PAN carbon fibres is extensive, around 183-286 MJ/kg (Song et al., 2009). It is much more important than for glass fibre fabrication with 13-32 MJ/kg (Song et al., 2009), principally used in. melting process. Furthermore, carbon fibre can have serious impacts to environment and to human health due to emissions from the oxidation and carbonization furnaces and industrial ovens such as hydrogen cyanide (HCN), ammonia (NH_3), nitrogen oxide (NOx), volatile organic compounds (VOCS), carbon monoxide (CO) and carbon dioxide (CO_2) (Grzanka, 2014).

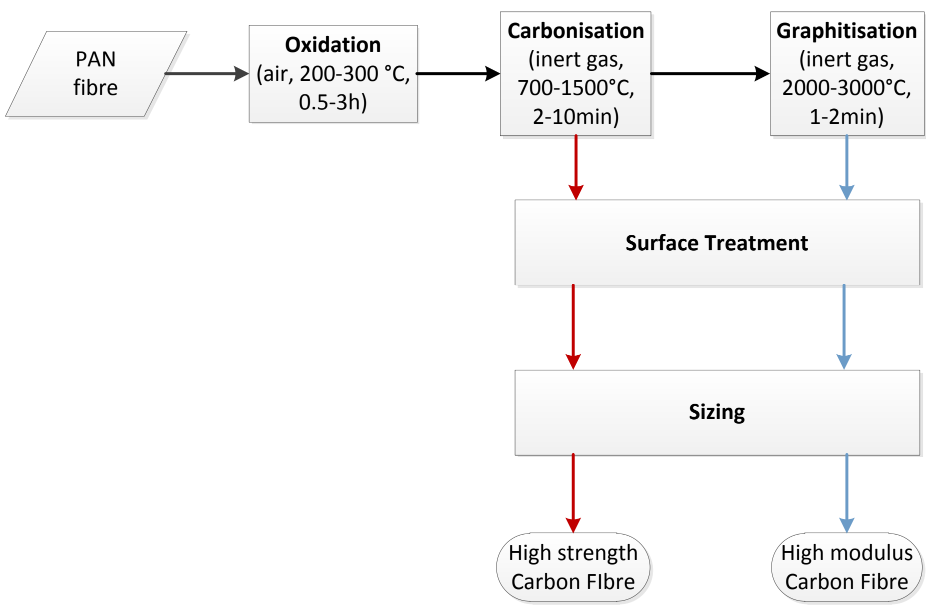


Figure 1-3: Principal steps of fabrication process of carbon fibre from PAN precursor(Dupupet, 2008)

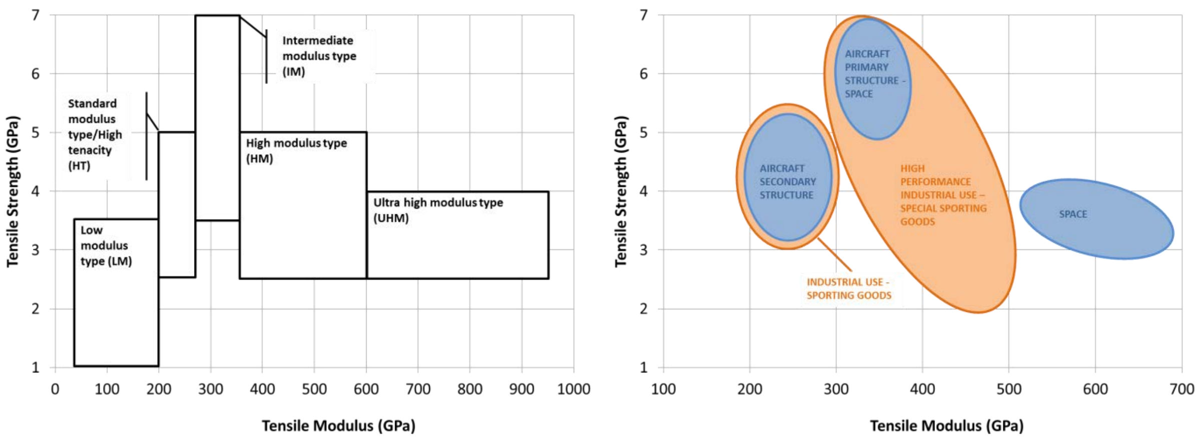


Figure 1-4: Principal ranges of carbon fibre (left) (The Japan Carbon Fiber Manufacturers Association - www.carbonfiber.gr.jp/english/material/type.html)and their applications (right) (Toray, 2012)based on mechanical properties

Table 1-2: Mechanical properties of E-glass fibre, Kevlar fibre and HM carbon fibre (Berthelot, 2012)

	E-Glass Fibre	Kevlar Fibre	HM Carbon Fibre
Density (g/cm^3)	2.6	1.4	1.8
Diameter (µm)	10-20	12	5-7
Tensile strength (MPa)	3400	3000	2800
Tensile Modulus (GPa)	73	60	400

1.2.3. Principles of FRP/CFRP Production

Although various matrices are employed in carbon fibre composites (carbon, ceramic, metal and polymer), CFRP including thermoset and thermoplastic matrix types, dominate the market with 64% contribution on total revenues of carbon fibre composites in 2014 which are estimated of 16.6 billion US$ (Witten et al., 2015) (see Figure 1-5). The use of thermosetting polymers as matrix in CFRP is more important than thermoplastics because of their good mechanical properties, temperature resistance… compared to thermoplastic matrix.

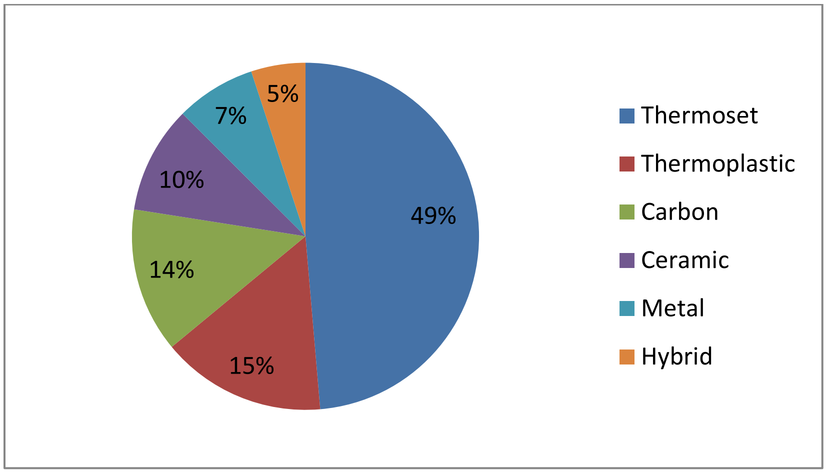


Figure 1-5: Repartition of revenues of carbon fibre composites by matrix types (Witten et al., 2015)

As fibres cannot be used directly in mechanical applications due to their small sections, polymeric matrix is used for three functions: binding fibres together, transferring mechanical loads to fibres and protecting fibres from external environment. There are two main types of polymeric matrix: thermoset and thermoplastic. Examples of thermosets and thermoplastics used in composite with their physical properties are presented in Table 1-3.

Thermosets are obtained by curing thermosetting polymers (pre-polymers) which are usually liquid or malleable. During the "curing", the chemical reactions (the molecular cross-linking process) occur between the chains of pre-polymer to form three dimensional networks. This process is irreversible and renders thermosets infusible, high thermal stability, good mechanical properties (stiffness, hardness). Since their shape is permanent, thermosets cannot be reprocessed by heating once cured/hardened. Principal thermosets used in composites in general are unsaturated polyester (UP), phenolic, epoxide, etc.

In opposite of thermosets, thermoplastics consisted of long linear polymer chains, are heat softenable, heat meltable and reprocessable. The process of thermoplastic composite is based on the change of phase of thermoplastic matrix from liquid to solid. The use of thermoplastics in composite results reduction of manufacturing cost in compared to thermosets. However, the applications of thermoplastic composites are limited because of their low thermal stability and weak mechanical properties in compared to thermoset composites. Some thermoplastics are used as matrix in composites: polyvinylchloride (PVC), polyethylene (PE), polypropylene (PP), polyamide, polycarbonate, etc.

Table 1-3: Physical properties of polymeric matrices (Berthelot, 2012)

	Unit	Unsaturated polyester	Phenolic	Epoxide	PP	Polyamide
Density	kg/m^3	1200	1200	1100-1500	900	1140
Tensile Modulus	GPa	2.8-3.5	_	3-5	1.4	2.5
Tensile Strength	MPa	50-80	40	60-80	20-35	60-85
Tensile Elongation	%	2-5	2.5	2-5		
Compressive Strength	MPa	90-200	250	_		
Shear strength	MPa	10-20	_	30-50		
Heat deflection temperature (1.8 MPa)	°C	60-100	120	290	50-60	65-100

The fabrication of Fibre Reinforced Polymer (FRP) Composites that in general includes CFRP must guarantee for the structure of composite:

1. The repartition of phases in composite, i.e. internal structure, by stratification and impregnation.
2. The form of composite for assemblage, i.e. external structure by moulding and finishing.

Carbon fibre in unidirectional (UD) tapes or fabrics form is impregnated in resin by two methods: wet lay-up and prepreg lay-up. In wet lay-up, impregnation of dry fibre in liquid polymer is carried out simultaneously with moulding process. Otherwise, in prepreg lay-up, these processes are separated in which a solid preform of dry fibre maintained in polymer matrix (prepreg) is moulded after that. In the second method, thermosetting resins are partially cured in prepreg which must be stored in freezer (-23°C) to retard curing process before moulding step. During impregnation, laying up layer by layer of carbon fibre or prepreg following fibre orientation of each ply is applied (Figure 1-6) and any entrapped air or vapour (called "voids") has to be removed to obtain the optimum mechanical properties of composite product. At the final step, consolidation of thermoplastic composite and curing of thermoset composite are accomplished by moulding. Autoclaves are necessary for curing of aerospace thermoset composite parts to reduce void volume less than 1% in high pressure (Bersee, 2010).

Apart from the main components (fibre, resin), different substances can be added in resin to improve properties of finished composite (e.g. flame retardant, conductive, antistatic, pigments, anti-UV…), to facilitate the manufacturing process (lubricants, release agents, anti-shrinkage…) or to reduce cost. The quantity of these products in composite varies from few percentages or less as additive to few dozen percentages as filler.

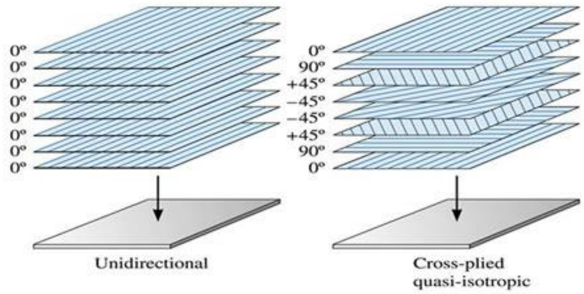


Figure 1-6: Examples of composite lay-up on fibre orientation (Quartus Engineering, www.quartus.com/resources/white-papers/composites-101)

1.2.4. FRP/CFRP production for Aerospace Sector

Table 1-4 summarised the principal fabrication processes for FRP composites in aerospace in which prepreg hand lay-up is the most used process (Bersee, 2010). As the lay-up of prepreg plies is achieved manually, prepreg hand lay-up requires intensively labour and allows a low volume. However, it is suited to produce large and complex items of aerospace parts. In order to reduce labour cost and improve the overall quality, automatic prepreg lay-up methods are developed: automated tape laying, fibre replacement. Filament winding is also an automatic lay-up process to produce closed and convex structures. In filament winding, continuous rovings or tows impregnated in resin before, during or after winding process are wound over a rotating mandrel. Based on wet lay-up principle, Liquid Composite Moulding processes are separated by the method of resin infusion in fibre, e.g. high pressures with two metal mould halves in Resin Transfer Moulding (RTM), a one sided mould closed by a vacuum bag in vacuum assisted resin transfer moulding. The thermoforming processes have the same principle of the metal or thermoplastic forming. The laminate is either partially or totally heated to the necessary processing temperature after which it is pressed into a mould by mechanical means or by hydrostatic pressure (Bersee, 2010). Chopped fibres can be used in composite thermoforming in Sheet Moulding Compound (SMC) or Bulk Moulding Compound (BMC) for the applications which do not need high mechanical properties.

Table 1-4: Composite Aerospace Manufacturing Processes (Bersee, 2010)

Wet lay-up	Prepreg lay-up
Filament Winding, Liquid Composite Moulding (infusion, Resin Transfer Moulding (RTM), vacuum assisted resin transfer moulding (VARTM))	Prepreg hand lay-up, Automated tape laying, Filament Winding, Fibre Placement, Thermoforming

1.2.5. Waste Generation in Aerospace CFRP Production

The fabrication of aerospace CFRP is very complex and can vary in function of numerous factors, from raw materials (e.g. precursors of carbon fibre), carbon fibre types/forms to functions of finished CFRP part (e.g. fuselage, rudder, aileron, etc.).

In function of the manufacturing processes, different wastes can be generated. The carbon fibre chain for aerospace CFRP will constitute the waste type concerned in CFRP waste management. Ex-PAN carbon fibre and thermoset matrix are the type of the studied CFRP wastes due to their popularity in carbon fibre production and aerospace applications. Figure 1-7 summarises the simplified ex-PAN carbon fibre life cycle in aerospace CFRP, from its production by PAN precursor in carbon fibre manufacturers, the fabrication of CFRP pieces through wet lay-up or prepreg lay-up, the assembly of CFRP pieces to aircraft to their retirement. As carbon fibre generated the most value in CFRP and CFRP recycling is aimed to recover carbon fibre, only wastes containing carbon fibre are considered in this study, including also dry fibre waste. Based on inputs and outputs of each step, the generated production wastes are dry fibre waste, uncured production waste and cured production waste from the abnormal items in output and the cutting wastes before and after the processes. The end-of-life waste comes from the retired aircraft through dismantling process.

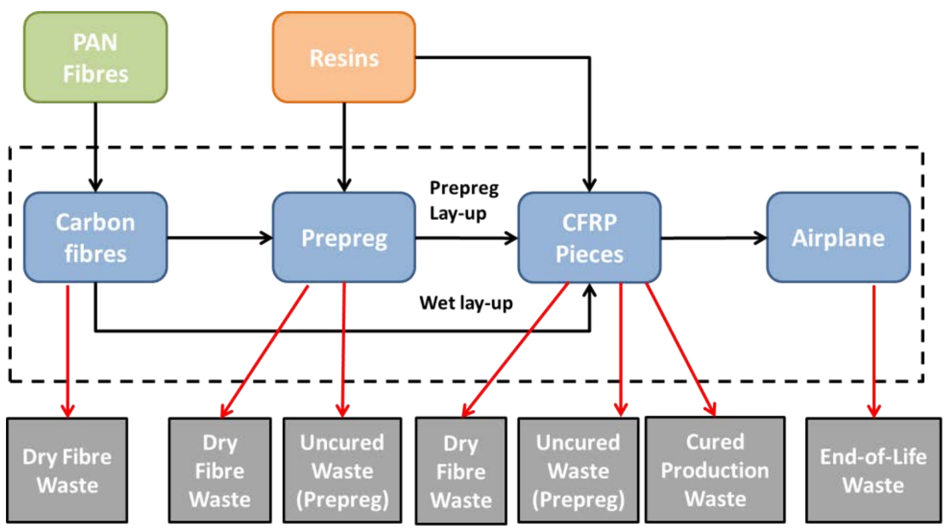


Figure 1-7: Simplified carbon fibre life cycle in aerospace CFRP

1.3. State of art of recycling techniques

Along with the increased future needs and stronger environmental legislations, several recycling technologies have been developed and proposed for composite materials over the past decades. Due to the high use of polymer-matrix composites in diverse sectors, the development of recycling technologies has been mainly focused on this type of composites. The recycling of thermoset composites is receiving a lot of attention due to the technical difficulties to separate the thermoset matrix from the reinforcement materials (Yang et al., 2012).

Table 1-5 proposes some recent works dedicated to develop recycling techniques for FRP in general and of CFRP more specifically. Figure 1-8 presents the CFRP recycling techniques and their recovered products. Different recycling techniques of FRP have been studied and developed in order to improve the recycling yield and the properties of the recovered fibre by three main types of techniques: mechanical, thermal, and solvolysis. Other recycling solutions can be found such as electrochemical (Sun et al., 2015) and biotechnological (Hohenstein Institute, 2015) techniques but they are less mature than other ones for CF recovery and rest at laboratory scale. Table 1-6 presents some typical features of some recycling techniques, i.e. the principle, the retention of strength tensile of recycled fibre as compared to virgin fibre and the scale of development of technique.

Table 1-5: Studied on Recycling techniques for FRP/CFRP

Recycling Techniques	Sources
Mechanical recycling (grinding, electrodynamic fragmentation)	(Pannkoke et al., 1998; Kouparitsas et al., 2002; Ogi et al., 2005, 2007, Palmer et al., 2009, 2010; Müller, 2013; Howarth et al., 2014; Suez environnement, 2015; Mativenga et al., 2016)
Thermal techniques (pyrolysis, fluidised bed, microwave)	(Fenwick, 1996; Kennerley et al., 1998; Pickering et al., 2000; Yip et al., 2001; Cunliffe et al., 2003; Lester et al., 2004; Gosau et al., 2006; Jiang et al., 2008; Meyer et al., 2009; López et al., 2012, 2013; Akesson et al., 2013; Obunai et al., 2015)
Chemical techniques	(Allred et al., 2001; Hyde et al., 2006; Piñero-Hernanz et al., 2008b, 2008a; Jiang et al., 2009; Nakagawa et al., 2009; Yuyan et al., 2009; Bai et al., 2010; Kamimura et al., 2010; Feraboli et al., 2012; Knight, 2013; Yuyan et al., 2009; Onwudili et al., 2013; Oliveux et al., 2013, 2015b; Okajima et al., 2014; Yildirir et al., 2014)
Other techniques (biotechnological, electrochemical, respectively)	(Hohenstein Institute, 2015; Sun et al., 2015)

Generally, all FRP have the same principles of recycling which focus on recover fibres from polymeric matrix, therefore, numerous CFRP recycling techniques are adapted and improved from other FRP, such as Glass Fibre Reinforced Polymer (GFRP). The recent review of (Oliveux et al., 2015a) is recommended for an exhaustive overview of the current FRP recycling techniques.

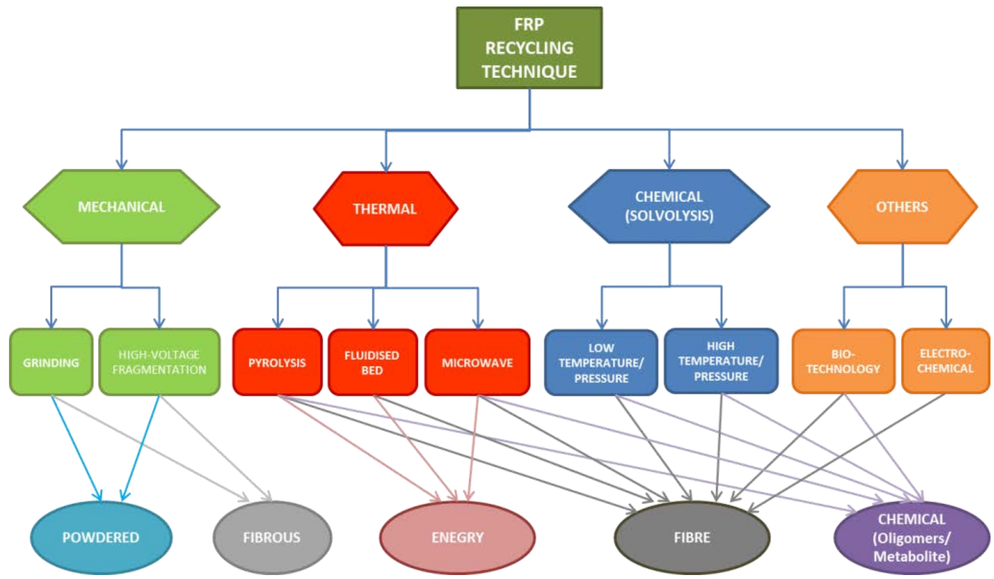


Figure 1-8: Summary of Recovered Products from the Recycling Techniques

Table 1-6: State of art of some recycling techniques

Technique	Principle of recycling	Scale of development	Retention Rate of Tensile strength of Recycled Carbon Fibre (%)
Grinding	Mechanical	Industrial (Oliveux et al., 2015a)	_
Pyrolysis	Thermal	Industrial (Oliveux et al., 2015a)	15-98 (Pimenta and Pinho, 2012)
Microwave	Chemical	Pilot (Akesson et al., 2013)	80 (Lester et al., 2004); 99 (Obunai et al., 2015)
Supercritical Water	Chemical	Pilot (Nakagawa et al., 2009; Oliveux et al., 2015a)	89-98 (Piñero-Hernanz et al., 2008a)

1.3.1. Mechanical recycling techniques

This group encompasses of the techniques in which fibre and matrix are separated by shredding (**grinding** technique, Figure 1-9) or high voltage pressure (**electrodynamic fragmentation**, Figure 1-10) without chemical reactions. After mechanical process and sieving, the obtained products are a mixture of matrix and fibre. They are separated into different fractions in function of the proportion and the length of fibre (Kouparitsas et al., 2002; Palmer et al., 2010), principally powdered resin-rich fraction and fibrous fibre-rich fraction.

Currently, grinding operates at industrial scale, especially for glass fibre reinforced composites: ERCOM (Germany) and Phoenix Fibreglass (Canada) or MCR (France) (Halliwell, 2006).

Although it is on pilot scale, electrodynamic fragmentation receives specific attention from aerospace industry in Germany (Müller, 2013), and in France with development of XCrusher™ process, specifically for CFRP waste of the start-up Camille (Suez environnement, 2015).

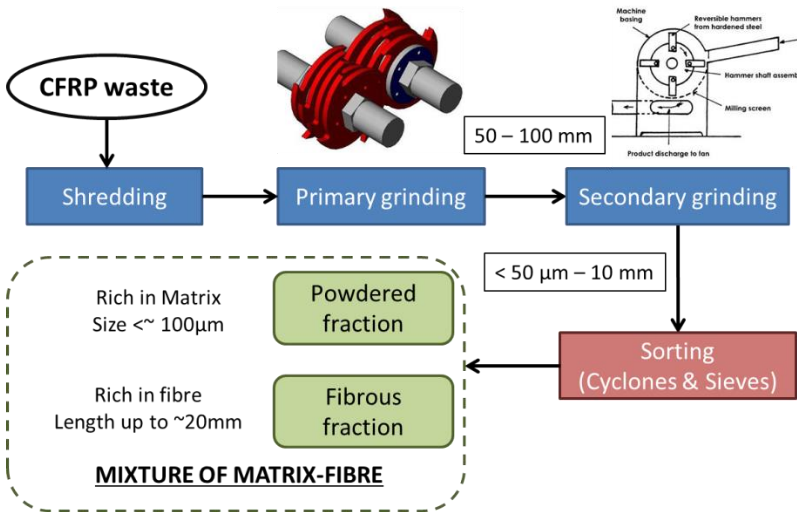


Figure 1-9: Principle of Grinding technique (Pickering, 2013)

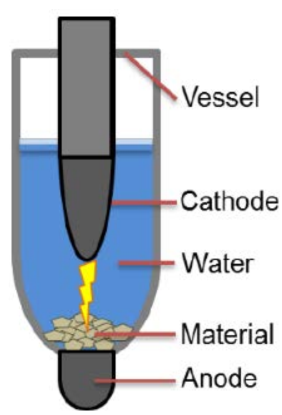


Figure 1-10: Electrodynamic fragmentation technique (Roux et al., 2013)

1.3.2. Thermal recycling techniques

Thermal techniques recycle fibres on decomposing matrix by heat (conventional pyrolysis, fluidised bed) or by microwave radiation (microwave) into heat or residual liquid. The gas fraction produced from the decomposition of matrix can be condensed to be reused as a fuel or burned to recover heat.

Pyrolysis is a thermal recycling process of FRP that decomposes the matrix at around 400 to 750 °C (Oliveux et al., 2015a) depending on the thermal properties of resin in order to recover fibres (Figure 1-11). The main characteristic of this process is the thermal decomposition in an inert environment or in a controlled atmosphere with a low proportion of oxygen to avoid the oxidation of fibres. A rapid gasification might be needed after the main process step to clean the fibres from char of resin decomposition (Davidson and Price, 2009; Meyer et al., 2009). Because of the process simplicity and due to the clean fibre recovery, pyrolysis has been industrialised all over the world: ELG Carbon Fibre (UK), CFK (Germany), MIT LLC (USA), Karborek (Italy), etc. (Oliveux et al., 2015a). However, it is hard and maybe impossible to treat the CFRP aircraft parts in this process due to their strong durability.

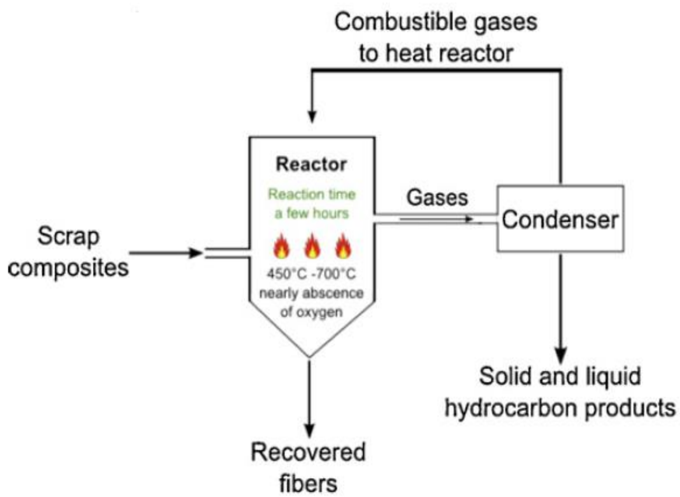


Figure 1-11: Pyrolysis technique (Morin et al., 2012)

In **fluidised bed** process (Figure 1-12), the sand is fluidised by the hot air flow at a temperature of 450-550 °C with a velocity of 0.4-1.1 m/s. In these conditions, the organic matrix is volatilised and the fibres are thus released. The fibres are sent out of the bed by gas flow. After the fibres are recovered, the gas passes through a secondary combustion chamber where the polymer is completely decomposed. Although recycled fibre can be damaged largely in the process, fluidised bed is suited to wastes contaminated on paintings or containing metal insert. This technique is still at both development stage and pilot scale (Yang et al., 2012).

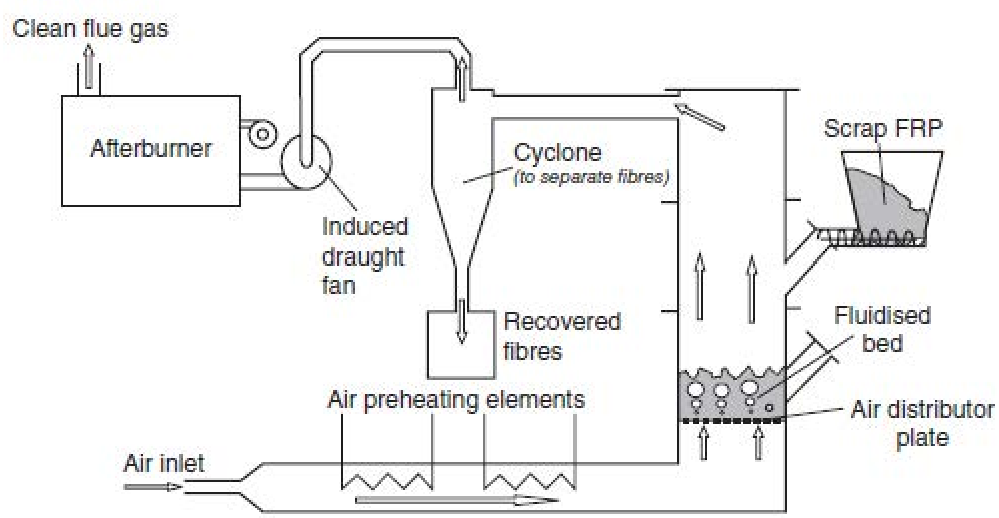


Figure 1-12: Schematic diagram of the fluidised bed process for recycling FRP composites(Jiang et al., 2008)

Microwave (Figure 1-13) has the principle in which the organic material will be heated and decomposed on gas and pyrolysis oil by microwave radiation, the inorganic part is then recovered. For composite, microwave has the advantage of heating through the bulk of the material (Akesson et al., 2013) and reducing the process energy with high-quality recycled fibre (Lester et al., 2004) compared to pyrolysis. For CFRP recycling, Firebird Advanced Materials (USA) developed a continuous microwave recycling method (Wood, 2010). This technique has also been studied and applied for GFRP: a continuous pilot plant for recycling of blades from wind turbine (Akesson et al., 2013) has been constructed by Stena Metall AB (Sweden).

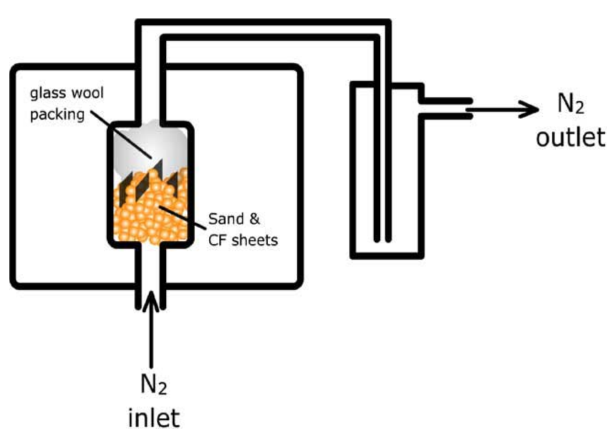


Figure 1-13: Microwave technique (Lester et al., 2004)

1.3.3. Solvolysis techniques

These techniques decompose matrix by chemical reactions in a solvent medium at atmospheric pressure or supercritical conditions (Figure 1-14). The polymer matrix is decomposed into different oligomers and the carbon fibre is recovered. Based on the operational conditions (solvent, catalysts, temperature and pressure), the fibre recovery rate and the time of operation can be varied. When temperature and pressure are above their critical point, fluids are in supercritical state with properties intermediate between liquid and gas phases: low viscosities, high mass transport coefficients, high diffusivities, and a pressure dependent on solvent power (Hyde et al., 2006). Besides the use of water, other supercritical solvents such as acetone, methanol, ethanol and propanol are also used for CFRP recycling because of their lower critical temperature and pressure compared to water (Piñero-Hernanz et al., 2008b). This technique has been industrialised for hazardous waste treatment since 1980s (Marrone, 2013). For composite application, it has received a lot of attention from academics and industry, and has been developed to pilot scale (Oliveux et al., 2015a).

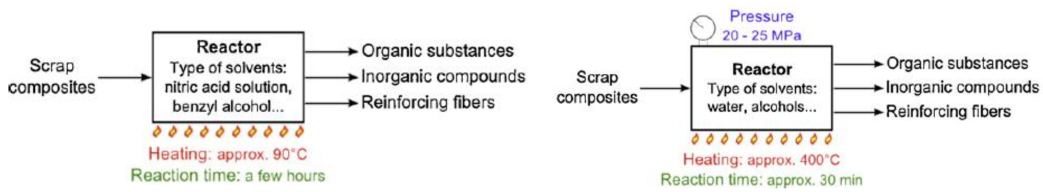


Figure 1-14: Solvolysis techniques for composites recovery, (left) solvolysis at low temperature and atmospheric pressure; (right) solvolysis in supercritical conditions (Morin et al., 2012)

1.4. Waste Management Framework

Modelling of waste management has been progressed through the development of waste treatment technologies and the evolution of assessment tools since 1970s (Morrissey and Browne, 2004). The early models of waste management worked have been developed with the objective of cost minimisation. The environmental assessment has received attention more recently. Although the sustainable waste management system needs to be environmentally effective, economically affordable and socially acceptable, there are very few studies that consider the social aspect (Achillas et al., 2013).

Different waste management strategies have been compared according to their level of performance in order to fulfil the defined criteria. Since the ranges and strategies in waste management are quite diverse, choosing a single waste management approach that satisfies the decision-makers' objectives is challenging. Indeed, a decision support framework is essential in order to support individuals or groups in their decisions toward achieving specific objectives, guide them to the best available solution, while it has enough flexibility to be modified (Karmperis et al., 2013). In waste management, decision support frameworks help to select the best available and applicable option(s) by analysing the selected waste streams and comparing the existing routes (Morrissey and Browne, 2004).

Most of current waste management models can be categorised by the assessment technique, into these three classes: cost benefit analysis (CBA), life cycle analysis (LCA) and multicriteria techniques (Morrissey and Browne, 2004; Karmperis et al., 2013). The strengths and the limitations of the three frameworks, which are summarised in Table 1-7, are well described in these two studies. The combination of these techniques in the assessment of a waste management model can be applied to get the advantages of each technique for an overall evaluation.

Table 1-7: Strengths and Limitations of the principal Waste Management Frameworks (Karmperis et al., 2013)

Technique	Strengths	Limitations
Cost-Benefit Analysis (CBA)	- Both direct and indirect long-term impacts (addition) - Uncertainty in the project's performance handled by risk assessment. - Suited to examine the project implantation by identification and evaluation of different technical options - Evaluation of project performance on behalf of concerned stakeholders through economic assessment	- Complex evaluation of non-economic indicators - Time-consuming for the development of a comprehensive CBA model. - Complex evaluation of the benefits and the costs of the project in ecosystems - Not adapted to the dynamic model (waste management strategies can change over time)
Life Cycle Assessment (LCA)	- The long term benefits in environmental protection from different options - Possible extension to economic assessment - Quantification of the emissions of activities and environmental impacts - Comparison of alternative scenarios for waste management strategies	- There are always additional scenarios in LCA apart from the studied scenarios. - The assumptions of LCA models (e.g. boundary conditions, data sources, impact assessment criteria, weights) may be subjective. - A sensitivity analysis is necessary for LCA models in case of high uncertainty from the limitations in data. - LCA does not specifically quantify impacts of eco-systems and species diversity.

Multi-criteria decision making (MCDM)	- Incorporation of multiple conflicting criteria into the management planning process - Use of both quantitative and qualitative criteria in multi-criteria decision making frameworks - Flexible method for evaluation of different assessment categories (e.g. economic, environmental, technical). - Consideration of the preferences of all stakeholders in the final result by assigning weights in each stakeholder.	- The evaluation results depend on criteria and their weight values which can be subjectively assigned.

The main applications of modelling involve waste management are planning of municipal solid waste management (MSWM), and various frameworks have been developed to support decision-making in MSWM:

They initially optimised individual sections of MSWM such as plant locations or delivery routes and later have developed to MSWM system (Hung et al., 2007). These decisions are often made by considering various criteria such as environmental impacts (e.g., global warming, human health risks, resource depletion, eco-system damage), associated economic costs and benefits, and regional characteristics (e.g., waste generation rate, and political and social factors) (Soltani et al., 2015).

Geographic Information Systems (GIS) have been integrated in waste management modelling for optimal sitting of waste treatment facilities (Siddiqui et al., 1996; Kao and Lin, 1996; Higgs, 2006; Al-Jarrah and Abu-Qdais, 2006; Şener et al., 2006; Gemitzi et al., 2007; Chang et al., 2008; Delgado et al., 2008; Tavares et al., 2011) and designing the network of collection (Ghose et al., 2006; Tavares et al., 2009; Zamorano et al., 2009; Zsigraiova et al., 2013).

The studies on the role of multiple stakeholders on MSWM designing have received also more attention since the past decades (Haastrup et al., 1998; Cheng et al., 2003; Hung et al., 2007; Khan and Faisal, 2008; Contreras et al., 2008; De Feo and De Gisi, 2010; Soltani et al., 2015)

Furthermore, the increasing interest on materials recovery (environmental consciousness, legislation, security of raw materials…) has motivated the integration of waste management in reverse supply chain for efficient materials management, e.g. electronic wastes (Achillas et al., 2010; Gomes et al., 2011), End-of-life vehicles (Chan et al., 2012; Ene and Öztürk, 2015).

1.5. Scientific Objectives and Motivation of the Study

There are currently no specific legislations for composite materials (Yang et al., 2012) (Yang et al., 2012) and retired aircraft (Van Heerden and Curran, 2011). However, composite wastes including aerospace CFRP waste can be concerned by the legislations through the regulations on the components of composite or the domain of applications (Pickering, 2006):

The European Directive on Landfill of Waste (Directive 1999/31/EC, 1999) targets for the reduction in the amount of organic material being landfilled, therefore concerning on polymeric composite . In many European countries, composite landfill is already illegal.

The End-of-life Vehicle Directive (Directive 2000/53/EC, 2000) regulates the disposal of vehicles and the requirements have been applied since 2015, 85% of the weight of all end-of-life vehicles must be reused or recycled, a further 10% may be subject to energy recovery and a maximum of 5% of the vehicle may be disposed of in landfill.

In this context, besides the works on technical recycling process, studies on life cycle assessment of FRP in general and on CFRP in particular have received a lot of attention in order to study the environmental benefits of FRP/CFRP that can be gained from the use of more conventional materials (Takahashi et al., 2002; Suzuki and Takahashi, 2005; Duflou et al., 2009; Song et al., 2009; Das, 2011; Witik et al., 2011, 2012, 2013) . However, these studies focused mostly on production and utilisation phases of such materials. The phase of waste treatment is poorly studied and limited to one technique, e.g. recycling by microwave (Suzuki and Takahashi, 2005; Das, 2011) or recovery energy by incineration (Witik et al., 2011).

Only very few studies on CFRP recycling techniques (Hedlund-Åström, 2005; Witik et al., 2013; Li et al., 2016) which include in-depth investigations on the structure of CFRP waste treatment can be found:

- (Hedlund-Åström, 2005) applied Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) in order to study waste treatments of End-of-life CFRP and other composites, with grinding, fluidised bed and incineration. As LCC and LCA of waste treatment phase depends on recovered products, the choice of replaced material between virgin carbon fibre and virgin glass fibre is the key factor of selection of the waste treatment technique. The benefit from incineration may be higher than the advantage of recycling if recycled carbon fibre is used to replace low value material, such as glass fibre. In reality, the characteristics of the recycling process may impact the quality of recovered fibre output, besides the type of origin fibre in waste.
- (Witik et al., 2013) studied the environmental impacts (climate change, resources, ecosystem quality and human health) of three waste treatment options, i.e., pyrolysis, incineration and

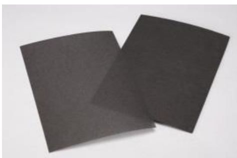
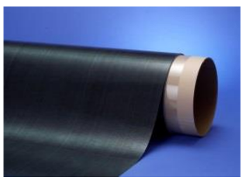
landfilling. A quantitative model has been developed for the determination of equivalent quantities of virgin carbon fibre and virgin glass fibre, which are replaced by RCF to achieve mechanical performance equivalent to virgin material in Sheet Moulding Compound (SMC) through the tensile modulus. However, the utilisation of RCF in polymeric matrix is a complex process depending on numerous criteria apart from the tensile modulus. Although the market of RCFs has not been mature due to the uncertainty of their mechanical properties compared to VCFs, their potential applications are numerous, not only in reinforcement purpose (Bulk Moulding Compound (BMC), Sheet Moulding Compound (SMC), thermoplastic composites, concrete…), but also in other applications which do not depend much on mechanical properties of materials such as electrical and electronic products, e.g. electromagnetic shield (Wong et al., 2010). Indeed, besides reinforcement use, carbon fibre can be found in numerous applications in various forms from filler in cement, housing equipment, heat insulator to anti-electrostatics sheets (Table 1-8).

– (Li et al., 2016) carried out a study on LCC and environmental assessment (GWP, energy use, final disposal waste) for End-of-life CFRP in automotive with three options (landfilling, incineration and mechanical recycling) within regulations of UK and EU. In this hypothetic case, between the two conventional disposal techniques (landfill, incineration), landfill tax can be viewed as a useful tool to shift CFRP waste from landfill to incineration because of the low GWP impacts and energy use in landfilling. Benefits of recycling depend on displacement factors of virgin carbon fibre by recycled fibre and on recycling rate in order to balance the energy-intensive recycling process. However, grinding process in mechanical recycling degrades fibres on reducing their length and cannot separate cleanly fibre and matrix from the composite. The carbon fibre recovery rate of one hundred per cent and the total displacement of virgin carbon fibre are impossible (Kouparitsas et al., 2002; Palmer et al., 2009).

Table 1-8: Usages of carbon fibres and their forms (The Japan Carbon Fiber Manufacturers Association-www.carbonfiber.gr.jp/english/material/usage.html)

	Types	Specifications	Major Usage
	Filament	A yarn constituted of numerous number of fibre: twisted, untwisted, twisted-and-untwisted	Reinforcement material for CFRP, CFRTP or C/C composites, having such usage as Aircraft/Aerospace equipment, sporting goods and industrial equipment parts

	Tow	An untwisted bundle of yarn constituted of extremely numerous number of fibre	Reinforcement material for CFRP, CFRTP or C/C composites, having such usage as Aircraft/Aerospace equipment, sporting goods and industrial equipment parts
	Staple Yarn	A yarn made of spinning of staples	Heat Insulator, Anti-friction material, C/C composite parts
	Woven fabric	A woven sheet made of filament or staple yarn	Reinforcement material for CFRP, CFRTP or C/C composites, having such usage as Aircraft/Aerospace equipment, sporting goods and industrial equipment parts
	Braid	A braided yarn made of filament or tow	Particularly suitable for reinforcement of tubular products
	Chopped fibre	A chopped fibre made of sized or non-sized fibre	Compounded into plastics/resins or Portland cement to improve mechanical performances, abrasion characteristics, electric conductivity and heat resistance
	Milled	Powder made by milling fibre in a ball-mill etc.	Compounded into plastics/resins or rubber to improve mechanical performances, abrasion characteristic, electric conductivity and heat resistance

	Felt Mat	A felt or mat made by layering up of staple by carding etc. then needle-punched or strengthened by organic binders	Heat insulator, base material for moulded heat insulator, protective layer for heat resistance and base material for corrosion-resisting filter
	Paper	A paper made from staple by dry or wet paper-making	Anti-electrostatics sheets, electrodes, speaker-cone and heating plate
	Prepreg	An intermediate material in a form of half-hardened sheets made of Carbon Fibres impregnated with thermosetting resin, qualities of which being stable and sustained long enough and therefore easily applicable for automatic sheet-layering	Aircraft/Aerospace equipment, sporting goods and industrial equipment parts needing lightness in weight and high performances
	Compounds	A material for injection moulding etc. made of mixture of thermoplastics or thermosetting resins added by various additives and chopped fibre and then being compounded	Housing etc. of OA equipment taking advantages of electric conductivity, rigidity and lightness in weight

These studies however focused on FRP/CFRP waste treatment pathways but do not consider a whole system of waste management involving a close network of waste owners/producers, recyclers and market for recovered products. In reality, due to the low value of market for recycled carbon fibre or to the shortage of waste flows, recyclers encounter difficulties in functioning in full capacity and may stop recycling operation. Figure 1-15 shows a primary snapshot presenting the principal producers/suppliers in CFRP industry: Airbus and Boeing sites with their partners, aircraft dismantling sites, and FRP/CFRP recyclers. In aerospace CFRP waste management system, the aerospace CFRP producers/suppliers, commercial aircraft manufacturers and aircraft dismantling sites are determined as the upstream of the system as wastes generated from these plants. The downstream begins with recyclers, and carbon fibre industry is also included in this part as the market for recycled carbon fibre.

Actually, aerospace CFRP waste management can be viewed not only at a global problem but also a local one due to the following reasons:

- As carbon fibres used in aerospace require excellent quality, there are very few aerospace carbon fibre producers, principally the Japanese groups. Besides the main sites in Japan, these groups have important plants in the world near the airplane manufacturing/assemblage sites of aircraft manufacturers.

- With the high demand of global air traffic, the number of airplane deliveries has been increasing rapidly and has spread all over the world in these recent years. Besides the two most important commercial aircraft manufacturers (Airbus, Boeing), the other companies have high potential of development in narrow body jet airliner and regional jet, such as Bombardier (Canada), Embraer (Brazil), Mitsubishi (Japan), Honda (Japan), Comac (China)… with exhaustive use of CFRP.

- With the high unfilled orders of deliveries, the aircraft manufacturers use the principle of subcontractors and suppliers all over the world to increase the productivity.

- The high increase of global air traffic industry poses the necessity of a dynamic and decentralisation system for the maintenance and dismantling of airplane instead of the centralisation system at the sites of aircraft manufacturers.

- The FRP/CFRP recycling industry has developed unequally in the world. Europe has more attention on this problem and has actively progressed in this domain.

Therefore, with the development of aerospace industry, aerospace CFRP wastes are generated all over the world, the production wastes may be produced principally on the aircraft fabrication zones including airplane manufacturers and their suppliers while the end-of-life waste from retired aircraft is present all over the world.

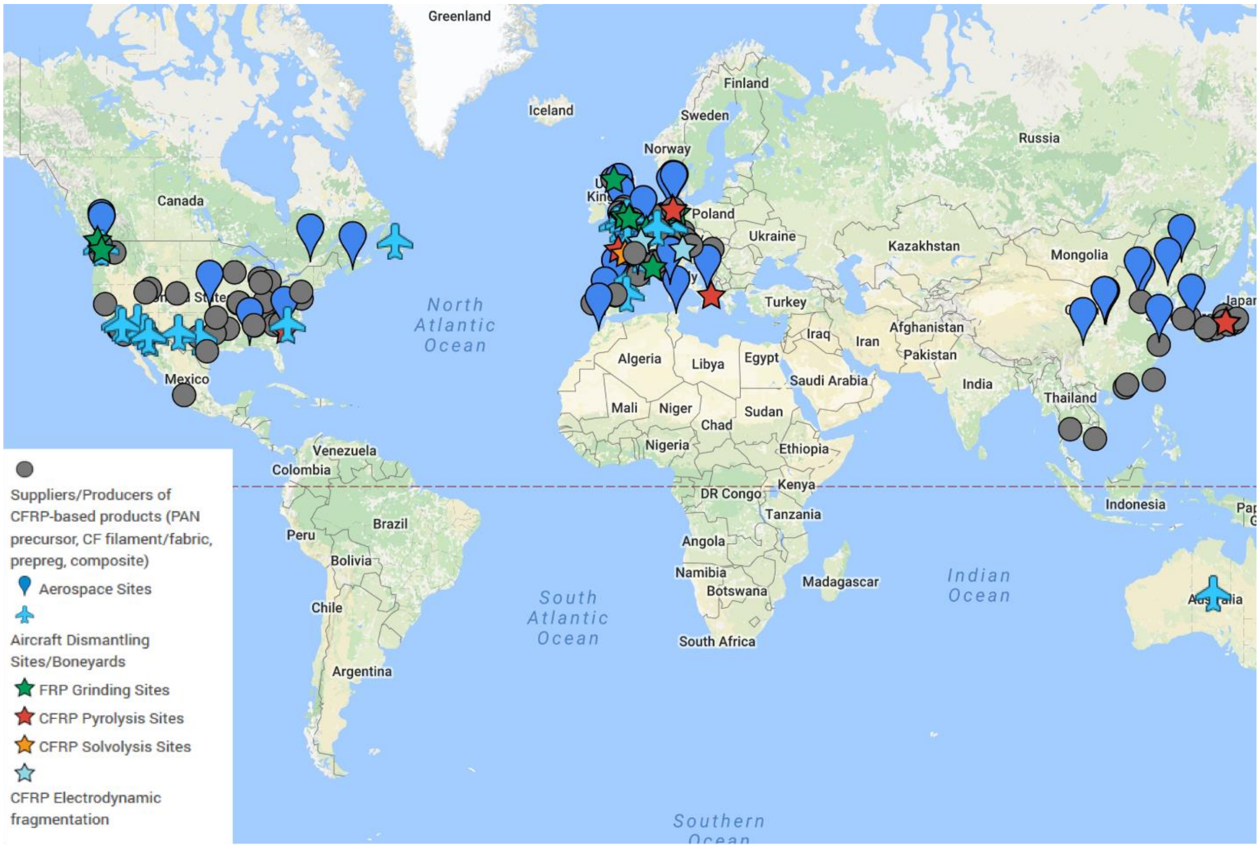


Figure 1-15: Global snapshot of principal CFRP producers/suppliers, commercial aircraft plants of Airbus –Boeing and their partners and the aircraft dismantling/storage sites

The projects of Airbus with PAMELA - TARMAC Aerosave and of Boeing with AFRA have initiated the development of solutions in response to these challenges of aerospace industry on waste management. However, these projects work exclusively on technical issues, there is no study on development of aid-decision making tools for stakeholders in complex aerospace CFRP waste management system. Within the framework of the SEARRCH project, the objective of this work is to develop a generic framework for the design of aerospace CFRP waste management. In particular, this study is focused on system modelling in order to develop a framework of optimisation for aerospace CFRP waste management taking into account economic and environmental criteria. For this purpose, this PhD manuscript is divided into six chapters (Figure 1-16):

- This introduction chapter (Chapter 1) is dedicated to literature review. The context of the study is highlighted: carbon fibre and CFRP material, recycling techniques and modelling frameworks of waste management
- Chapter 2 presents the methods and tools that will be applied in the body of the study.

- The modelling of aerospace CFRP waste management focuses on waste treatment without consideration of the whole system with waste collection and distribution of recovered products. The economic and environmental assessments of different technical routes are carried out with various indicators represented the viewpoint of several stakeholders in Chapter 3. Besides recycling techniques, the non-fibre recovery techniques (landfill, incineration and co-incineration) are included in the analysis to evaluate their economic and environmental interests compared to fibre recovery techniques. As only the characteristics of process are taken into account in this part, only cured CFRP production waste is considered.
- A complete aerospace CFRP waste management is modelled in Chapter 4, including waste collection, waste treatment and distribution of recovered products. The characteristics of the model are based on the context of the studied system, i.e. generation of waste types (dry fibre waste, uncured production waste, cured production waste, end-of-life waste), the compatibility of waste type and treatment technique, the generation of recovered products through different recycling techniques, the quality of recovered products and the requirement of each market. This is a static model based on mono-period (one year) approach by Linear Programming (LP) with the existing waste treatment plants in the system. A bi-criteria optimisation with minimisation of cost as an economic criterion and minimisation of GWP impact as an environmental criterion for the whole system is coupled with a multi-criteria decision making (MCDM) tool to develop a relevant configuration of waste collection and allocation of different techniques for the system. The modelling and optimisation is carried out for a case study of France.
- Chapter 5 present an extended model of Chapter 4 considering time impact on decision making and economic profits from recovered products in waste management. A multi-period model is developed to take into account the variation of wastes over time. Different waste scenarios are modelled to consider the impacts of the different trends on evolution of waste quantity in the horizon time. Mixed Integer Linear Programming (MILP) is used to model this system and allows deployment of new recycling sites to treat all waste flows in the horizon time considered. The characteristics of the network is the same as in Chapter 4: generation of waste types (dry fibre waste, uncured production waste, cured production waste, end-of-life waste), compatibility of waste type and treatment technique, generation of recovered products through different recycling techniques, quality of recovered products and the requirement of each market. As the market of recycled carbon fibres and their prices strongly depend on their applications, a bi-criteria optimisation process for economic and environmental assessments is carried out in order to study the potential economic profit of recycling industry. A first optimisation scheme follows the same

principle of optimisation as Chapter 4: minimisation of cost and minimisation of GWP impacts. The different ranges of price for recycled carbon fibres are then determined according to the cost and GWP impacts in the optimised system. Based on these values, a range of fixed prices is imposed on recycled carbon fibre to carry out a second bi-criteria optimisation scheme in which the objectives involves the maximisation of Net Present Value (NPV) and minimisation of GWP impacts. The Multiple Choice Decision Making techniques (M-TOPSIS and PROMETHEE) are used to determine the relevant strategy in each waste scenario in the system, i.e. low price of recycled carbon fibre, high NPV of the system and low GWP impacts of the system.

– Finally, the conclusions and perspectives in Chapter 6 will end this manuscript.

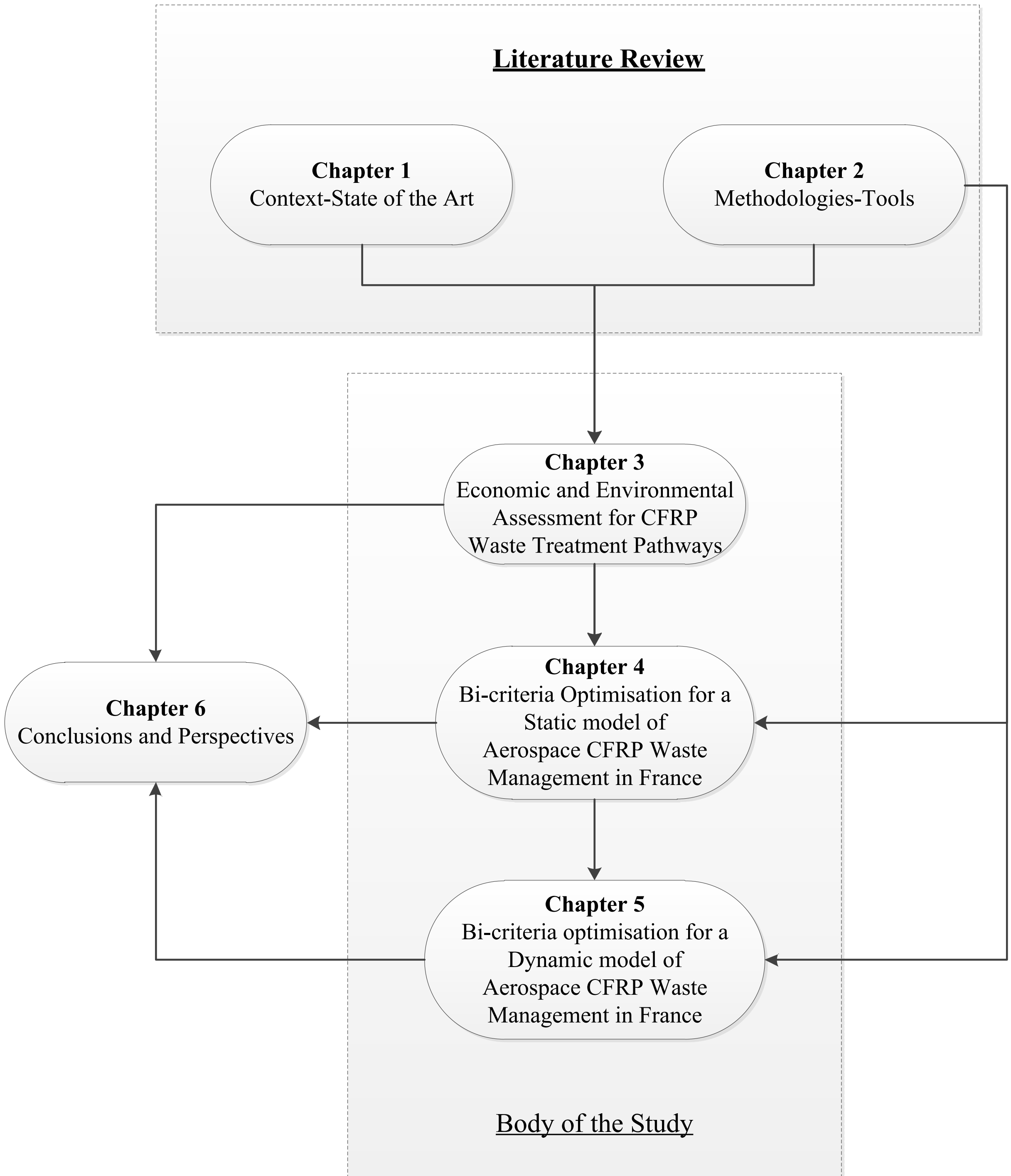


Figure 1-16: Structure of this PhD thesis

CHAPTER 2

Methods and Tools for CFRP Waste Management Optimisation

Abstract

This chapter presents the methods and tools that are used in the modelling and optimisation of the aerospace CFRP waste management system that is developed in this work. They contribute to the methodological framework of Chapters 3, 4, and 5. The specification of the problem formulation will be detailed in each dedicated chapter. The modelling principles and the different optimisation approaches are described in this chapter with economic and environmental assessment that will be embedded in the the multi-objective optimisation strategy applied in this study. This framework will permit to identify the relevant configuration for both economic and environmental objectives taking into account the waste types, treatment technologies, recovered products, deployment time and spatial allocations. The numerical tools that will be used for modelling and optimisation of the waste management system as well as the decision-aid methods and spatial data collection/representation are briefly presented hereafter.

Résumé

Ce chapitre présente les méthodes et les outils qui sont utilisés dans ce travail pour la modélisation et l'optimisation du système de gestion des déchets de CFRP aéronautique. Ils constituent le cadre méthodologique des chapitres 3, 4 et 5. Les caractéristiques spécifiques à la formulation de chaque problème traité seront présentées dans chaque chapitre. Les principes de modélisation et les différentes approches d'optimisation sont décrits ici ainsi que les méthodes d'évaluation tant économique qu’environnementale et la stratégie d’optimisation multicritère retenue. Cette approche permettra de déterminer la configuration pertinente satisfaisant les objectifs économiques et environnementaux en prenant en compte les types de déchets, les technologies de traitement, la valorisation des produits, le déploiement dans le temps et l’allocation spatiale. Les outils numériques utilisés pour la modélisation, et l’optimisation du système de gestion des déchets, l'aide à la décision et la collecte / représentation de données spatiales sont brièvement présentés.

2.1. Introduction

The aim of this study is propose a generic framework for modelling and optimising aerospace CFRP waste management considering economic and environmental criteria. Indeed, the processes of modelling and assessment are firstly carried out to develop the studied system and to evaluate the indicators. The studied system has multiple inputs (waste types), multiple treatment routes, and multiple outputs (recovered products). It must be evaluated according to multiple criteria involves multiple stakeholders at multi-scale (both temporal and spatial).

The allocations of different wastes in various techniques and the generation of recovered products will involve the satisfaction of mass balances that can be formulated by linear relationships. Therefore, linear programming techniques appear as good candidates for the modelling of aerospace CFRP waste management system.

A multi-objective optimisation formulation will be particularly sound to consider simultaneously the optimisation of an economic objective and an environmental objective, in order to determine the optimal configuration of the system. The allocation of wastes to be treated among the available techniques, and the implementation of new recycling plants (location, time, technique, and scale) in the system will be treated by this generic framework. Different approaches in modelling, assessment and optimisation are reviewed in this chapter in order to select and justify the methods used throughout this manuscript. This chapter is dedicated to a guideline of methodologies which are applied in function of the scope of each chapter in the body of this thesis.

This chapter is constituted of six sections. Section 2.2 presents the key ideas of the problem formulation through mathematical modelling and optimisation approaches. As bi-criteria optimisation approach will be applied for aerospace CFRP waste management in Chapter 4 and Chapter 5, the frameworks of multi-objective optimisation and the multi-criteria aid-decision methods are reviewed in Section 2.3. Besides, the evaluation methods used for economic and environmental assessments will be briefly described in Section 2.4. Section 2.5 is focused on the numerical tools for modelling, optimisation, environment assessment and spatial visualisation applied in this thesis.

2.2. Problem Formulation

2.2.1. Modelling Approaches

Modelling of real-life problems to mathematical models has been applied through human history to improve their every-day life, in architecture, astronomy, economy for example. Their functions are various, principally for phenomena explanation (physics, economics), predictions, and decision aid.

Indeed, in a formalised mathematical language, mathematical models can be analysed on a precise way by means of mathematical theory and algorithms.

The general concept of mathematical models consists of variables which represent the unknown or the modifiable parts of the model, correlations of different parts written down by equations or inequalities and data for numerical value specifying instances of the model. The modelling process is carried out in a cycle of the successive steps (Figure 2-1): building, studying, testing and use. Any defects found at the studying and testing stages are corrected by returning to the building step, and then any modifications of the model must be re-evaluated in studying and testing.

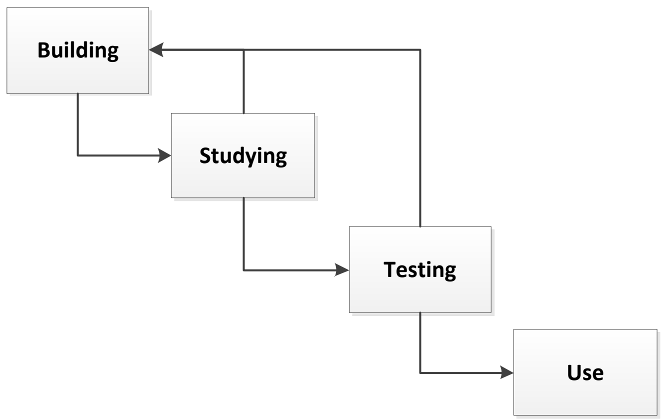


Figure 2-1: Process of mathematical modelling (Marion, 2008)

2.2.2. Optimisation Approaches

The advances in computer technology and the enormous gain in storage capacity and speed have led to more complex and bigger models, especially for optimisation problems. Based on mathematical modelling, an optimisation problem is developed by four key components: data/parameters, variables, constraints and objective function.

The optimisations problems are used to minimise or maximise a quantity associated with a decision process (objective) by exploiting available degrees of freedom (variables) under a set of restrictions (constraints) in different applications (data), such as process design, production, supply chain… After modelling by a programming language, or spreadsheet approaches, or algebraic modelling languages, optimisation problem is solved by a solver, i.e. a piece of software implemented algorithms.

The main categories of optimisation models can be classified by the following characteristics in modelling and optimisation (Figure 2-2):

- Randomness of data: uncertainty of data is not considered in deterministic models which are well studied but could be trapped in a local optimum and need exhaustive time of optimisation for the global optimum. Stochastic methods, such as genetic algorithms and simulated annealing allow a certain degree of randomness so as to increase the diversity off the solutions and also to avoid being trapped in a local optimum (Collette and Siarry, 2013).

- Linearity of correlations: relationships in optimisation models can be mathematically formulated to totally linear functions or to some non-linear functions. Besides continuous variables, integer variables are used to determine whether the decision is made or not in Mixed Integer Non-Linear Programming (MILP) or Mixed Integer Non-Linear Programming (MINLP) Problems. Linear Programming (LP) and Non-Linear Programming (NLP) are referred to linear or non-linear respectively problems containing only continuous variables.

The formulation of LP and MILP problems that are used in this study is presented hereafter:

<u>LP model:</u> Minimise $\sum_{j=1}^{n} c_j \times x_j$ (***x***$_j$ is variable)

Subject to $\sum_{j=1}^{n} a_{ij} \times x_j \le h_i$, $i = \{1, ..., m\}$

Where $\vec{x} \in \mathbb{R}^n$, $\vec{c} \in \mathbb{R}^n$ (***n*** is the number of variables of the problem)

$\vec{h} \in \mathbb{R}^m$ (***m*** is the number of inequality constraints)

<u>MILP model:</u> Minimise $\sum_{j=1}^{n} c_j \times x_j + \sum_{k=1}^{m} d_k \times y_k$ ($\boldsymbol{x_j}$, $\boldsymbol{y_k}$ are variables)

Subject to $\sum_{j=1}^{n} a_{ij} \times x_j + \sum_{k=1}^{m} b_{ik} \times y_k \le h_i$, $i = \{1, ..., o\}$

Where $\vec{x} \in \mathbb{R}^n$, $\vec{c} \in \mathbb{R}^n$ (***n*** is the number of continuous variables of the problem)

$\vec{y} \in \mathbb{Z}^m$, $\vec{d} \in \mathbb{R}^m$ (***m*** is the number of integer variables of the problem)

$\vec{h} \in \mathbb{R}^o$ (***o*** is the number of inequality constraints)

LP is powerful for the efficient allocation of limited resources in well-known activities in order to reach the desired goals, e.g. minimisation of cost or maximisation of profits. Besides the use of integer variables in MILP allows considering counts, decisions or logical relations in problems. Indeed, MILP is useful in strategic planning, supply chain management, energy industry planning, engineering design and production scheduling, etc. (Kallrath, 2000).

- **Temporal variation**: the variation of data following a time unit in the horizon time of the model is considered (dynamic) or not (static). Dynamic models are suited in long-term planning while static models are used to study configurations of the models or stable scenarios.

- **Planning level**: following the increase in detail level and the decrease of time scales, three planning levels can be distinguished: strategic (for plants, years), tactical (for production, months), and operational (for unit operation, weeks/days). Each planning level requires certain precision of data in modelling to develop optimal configurations: installed capacities/plant location/technology selection (strategic), resource-production-distribution planning/inventory control (tactical), materials flows/production scheduling (operational).

- Number of objectives in optimisation:

Mono-objective problems refer to the model in which only one objective function is optimised and then a myopic optimal solution can be determined. The formulation of mono-objective can be generalised as below (Collette and Siarry, 2013):

Minimise $f(\vec{x})$ (objective function)

Subject to $\vec{g}(\vec{x}) \leq 0$ (***m*** inequality constraints)

and $\vec{h}(\vec{x}) = 0$ (***p*** equality constraints)

where $\vec{x} \in \mathbb{R}^n$, $\vec{g}(\vec{x}) \in \mathbb{R}^m$, and $\vec{h}(\vec{x}) \in \mathbb{R}^p$

The multi-objective problems have no single solution but a set of points. The formulation of multi-objective can be generalised as below (Collette and Siarry, 2013):

Minimise $\vec{f}(\vec{x})$ (objective functions)

Subject to $\vec{g}(\vec{x}) \leq 0$ (***m*** inequality constraints)

and $\vec{h}(\vec{x}) = 0$ (***p*** equality constraints)

where $\vec{x} \in \mathbb{R}^n$, $\vec{f}(\vec{x}) \in \mathbb{R}^k$, $\vec{g}(\vec{x}) \in \mathbb{R}^m$, and $\vec{h}(\vec{x}) \in \mathbb{R}^p$

The literature review on CFRP recycling techniques, aerospace CFRP industry and waste management modelling frameworks shows the difficulties of modelling and optimisation of aerospace CFRP waste management. The confident characteristics of aerospace sector and the all “fresh” CFRP recycling techniques on pilot and laboratory scales make hard access on data for modelling. Besides, the global markets for recycled carbon fibre have not been yet mature to promote optimisation of finely detailed system to operational approach. However, aerospace CFRP waste management has suffered the lack of a generic framework for modelling and optimisation to sustainable development. Generally, waste management systems are modelled as linear problems based on mass balance through waste collection, waste treatment. Indeed, in this work, the system is modelled as LP (Chapter 4) and MILP (Chapter 5) problems for strategic planning (year scale) under bi-criteria optimisation, i.e. economic and environment objectives. Due to the lack of available data, deterministic modelling is proposed to generalise the framework. Static and dynamic approaches are also considered to study the impacts of waste evolution over time in the model.

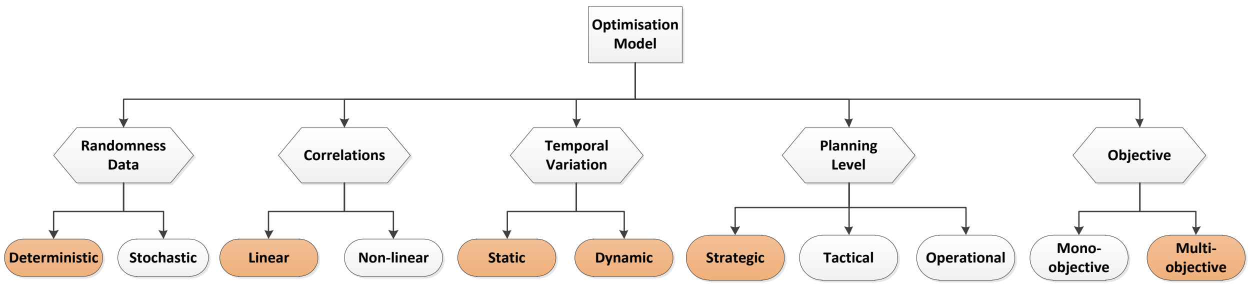


Figure 2-2: Taxonomy of optimisation models

2.3. Multi-Objective Optimisation Methods

Multi-objective optimisation allows setting up a set of solutions, not a unique solution like mono-objective optimisation. In multi-objective optimisation problem, a Pareto front is thus developed in order to represent in solution space the non-dominated vectors of Pareto optimal solutions. These solutions (so-called non-inferior, admissible or efficient solutions) cannot be improved in one objective function without declining the performance in at least one of the rest objectives (Van Veldhuizen, 1999).

The final solution that is selected must reflect preferences of decision makers with respect to the compromises between objective functions. As it is hard to define the domination relation a preference for one objective function against another one, various multi-objective optimisation methods can be classified into three main families of methods for solving multi-objective optimisation problem (MOP) according to the involvement of the decision marker is made in the optimisation process (Collette and Siarry, 2013):

- a priori preference methods are used when the problem is well established with high precision and the preferences are related to the objective functions before the optimisation process.

- a posteriori preference methods are used when there is no much knowledge about the problem, the optimisation process generate the trade-off surface covered with a finite number of solutions and the preferences are imposed after optimisation to select the compromise solution.

- progressive preference methods are used when the preferences are applied during the optimisation process.

For this study on CFRP waste management, hybrid method combined a priori and a posteriori is proposed to study separately the trade-off surface (Pareto front) of the criteria and the impacts of the objective preferences in the model. This approach is similar to the methodology used in hydrogen supply chain by (De León Almaraz, 2014).

Because no preference weight of criterion is imposed in optimisation process, lexicographic and ε-constraint of a priori preference methods are used firstly to build Pareto front.

2.3.1. Lexicographic method

Lexicographic method transforms MOP into single objective optimisation problem by optimising one objective function after the other (Coello, 1996):

Minimise	$\vec{f}(\vec{x})$	➡	Minimise	$f_1(\vec{x})$	➡	Minimise	$f_2(\vec{x})$
with	$\vec{g}(\vec{x}) \le 0$		with	$\vec{g}(\vec{x}) \le 0$		with	$f_1(\vec{x}) = f_1^*$
and	$\vec{h}(\vec{x}) = 0$		and	$\vec{h}(\vec{x}) = 0$			$\vec{g}(\vec{x}) \le 0$
			=>	$f_1(\vec{x}) = f_1^*$		and	$\vec{h}(\vec{x}) = 0$
						=>	$f_2(\vec{x}) = f_2^*$

⬇

Minimise	$f_k(\vec{x})$
with	$f_1(\vec{x}) = f_1^*, \ldots, f_{k-1}(\vec{x}) = f_{k-1}^*$
	$\vec{g}(\vec{x}) \le 0$
and	$\vec{h}(\vec{x}) = 0$
=>	the last value of $\vec{x}$ is the one which minimises all the objective functions

Therefore, the optimisation process of lexicographic method is carried out in a hierarchical order of importance of the criteria, beginning with the most important objective to less important one. This method is simple to apply and has computational efficiency. However, it tends to favour certain objectives, thus the Pareto front converges to a particular region. The distinct lexicographic optimisations with distinct sequences of objective functions does not produce the same solution (Collette and Siarry, 2013). Regarding its characteristics, the lexicographic method is used to determine the extreme solutions in Pareto front.

For example, for the bi-criteria optimisation problem of minimisation of total cost and GWP (Chapter 4 and Chapter 5), the lexicographic method allows determining the solution which has the minimal cost of the system with the lowest GWP value because with the same value of cost, higher GWP values can be obtained. Similarly, for minimisation of GWP, the solution, which has the minimum of GWP of the system with the lowest cost corresponding to this value of GWP, can be found by the lexicographic method.

2.3.2. The ε-constraint method

The ε-constraint method optimises one objective by transforming all other objectives function into inequality constraints (Miettinen, 1998):

$$\begin{array}{ll} \text{Minimise} & \vec{f}(\vec{x}) \\ \text{with} & \vec{g}(\vec{x}) \le 0 \\ \text{and} & \vec{h}(\vec{x}) = 0 \end{array} \quad \Rightarrow \quad \begin{array}{ll} \text{Minimise} & f_1(\vec{x}) \\ \text{with} & f_2(\vec{x}) \le \varepsilon_2 \\ & \ldots \\ & f_k(\vec{x}) \le \varepsilon_k (\varepsilon_i \ge 0 : \text{constraint vector, } i \in \{2,...,k\}) \\ & \vec{g}(\vec{x}) \le 0 \\ \text{and} & \vec{h}(\vec{x}) = 0 \end{array}$$

This method permits to inspect the original feasible region of solution surface and to produce non-extreme efficient solutions. Another advantage of the ε-constraint method is that we can control the number of the generated efficient solutions by adjusting the number of grid points in each range of the objective functions.

Between the two extreme solutions from lexicographic method, the other alternatives in Pareto front are obtained by the ε-constraints method, for example, the economic objective (minimising cost or maximising NPV) is optimised while the GWP values are limited under successive intervals.

2.3.3. MCDM methods

2.3.3.1. M-TOPSIS method

Then, Pareto selection, a posteriori preference method, is used to select the compromise solution in Pareto front of this bi-criteria optimisation problem. The weight of each criterion is considered in this step on using M-TOPSIS method. This multi-criteria decision making (MCDM) method is used to rank the Pareto optimal solutions.

The M-TOPSIS method is elaborated by (Ren et al., 2007) from the concept of original TOPSIS (Hwang and Yoon, 1981) which is to choose a solution that is closest to the ideal solution (better on all criteria) and far from the worst (which degrades all criteria). The modification in M-TOPSIS method allows avoiding rank reversals and solving the problems on evaluation failure when alternatives are symmetrical that often occurs in original TOPSIS. M-TOPSIS method which is detailed in the work of (Ren et al., 2007) (see Appendix 6). After normalisation step, the positive ideal solution (a_{ij}^{+}) and the negative ideal solution (a_{ij}^-) are identified for each objective. Then the Euclidean distances of each solution from the positive ideal solution and from the negative ideal solution, respectively D_i^+ and D_i^- are determined to form the D^+D^- plane. The point $(D_i^+D_i^-)$ represents each alternative ***i*** ($i = 1, 2, ..., n$) and the point ***A*** $\left(\min\left(D_i^+\right), \max\left(D_i^-\right)\right)$ is 'the optimised ideal reference point'. The Euclidean distances from the alternatives to the point ***A*** is used to establish the ranking order of all alternative in which the M-TOPSIS solution has the lowest distance to the point ***A***.

In this study, the two criteria are considered to have the same importance weight; there is no preference one criterion over the other.

2.3.3.2. PROMETHEE-GAIA

In Chapter 5, PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation), is used to determine the relevant strategy for three criteria, i.e. minimisation of recovered carbon fibre price, NPV maximisation and GWP minimisation.

Different from M-TOPSIS approach which is based on the order preference by similarity to ideal solution, PROMETHEE permits to study the relations between alternatives through their pairwise comparisons. A preference function is computed for with selected indifference and preference thresholds, as well as the imposed weight for each criterion in order to determine the preference relation of an alternative ***i*** over the other ***i'***. The six preference functions proposed in PROMETHEE can be adapted in different types of criteria, both quantitative and qualitative criteria can be handled in this method. Another advantage of PROMETHEE is that it can classify the alternatives which are difficult to be compared because of a trade-off relation of evaluation standards as non-comparable alternative (Athawale and Chakraborty, 2010).

Moreover, GAIA (Geometrical Analysis for Interactive Aid) which is the descriptive complement of PROMETHEE, permits to visualise the conflicts among the criteria, to identify the potential compromise and to fix priorities on observing the performance of solutions for each criterion based on their relative positions. The description of successive step in PROMETHEE can be found in Appendix 7.

An exhaustive study of different MCDM methods in process system designing can be found in the work of (Morales Mendoza, 2013).

2.4. Assessment methods

2.4.1. Environmental Assessment

Several methods and tools are available to assess environmental impacts and can help for decision support: Ecological Footprint (EF), Environmental Impact Assessment (EIA), Material Flow Analysis

(MFA), and Life Cycle Assessment (LCA) (Finnveden and Moberg, 2005). LCA is viewed as a mature, systems-oriented and analytical tool assessing potential impacts from products or services using a life cycle perspective. This study is focused on the impacts of CFRP waste treatment techniques, so that LCA methodology is particularly relevant to address the interest of recycling/recovery inside the whole supply chain and the avoided impact from a sequence only based on virgin CFRP production.

In LCA, the assessment of environment impacts is normalised by ISO 14040-44 following a four-step iterative process (Figure 2-3): goal and scope definition, Life Cycle Inventory (LCI), impact assessment (LCIA) and interpretation.

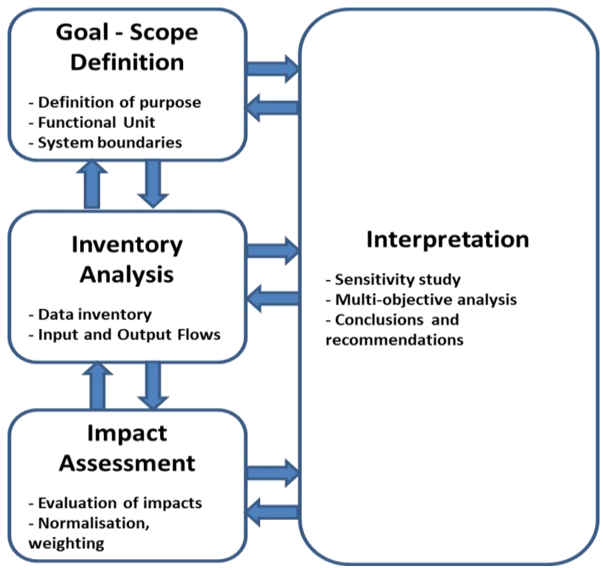


Figure 2-3: Life Cycle Assessment (LCA) Framework (ISO 14040-44)

By definition, LCA is a multi-criteria-oriented analysis and gives the opportunity to assess a wide range of indicators, such as Global Warming Potential (GWP), acidification, eutrophication, land-use, etc… A product life cycle consists in four individual phases: raw material extraction, production, utilisation and end-of-life (EOL). Within the limits of this study, only the environmental impacts of the EOL activities of the composite are assessed so the whole life cycle is not considered. The functional unit (FU) defined in LCA is 1 kg of waste to be treated by one of the proposed technology. Data on the input requirements (energy, other utilities) and output (recovered product, emissions) of all the activities in the system are collected for the studied model.

The lack of data concerning the other environmental indicators for CFRP waste management has hampered the extension of the methodology to a multi-criteria environmental approach even if the principle of LCA is still valid. Even if only GWP is considered, the conceptual framework of LCA as a system-oriented environmental assessment method could be extended to other criteria.

2.4.2. Economic Assessment

Based on the same principle of Life Cycle Assessment, economic assessment is carried out within the system boundary to evaluate the economic indicators with the elementary economic data of all included activities for functional unit of 1 kg of waste to be treated by one of the proposed technology.

Different indicators are studied in the analysis of waste treatment techniques (Chapter 3) and the optimisation of waste management system (Chapter 4 and Chapter 5) in order to represent different economic viewpoints of stakeholders in the system. For example, the total cost including transport, recycling, and disposal costs of the system is important for system planner/government, while the average cost price of recycled fibre is essential for decision making of recyclers, investors and especially for insertion in markets. Besides, the separation of operation cost and investment cost in this study permits to identify the economic weakness and strength of the waste treatment pathways in the system so that the improvement on process efficiency or plant scale can be proposed.

The assessment frameworks of these indicators are presented in detail in the dedicated chapters.

2.5. Numerical tools

2.5.1. Optimisation software

LP/MILP problems are usually solved by algorithms based on the simplex method and barrier methods which are available in most optimisation software packages. In this study, the mathematical modelling and optimisation process are made under GAMS (General Algebraic Modeling System) v.24.4.6 environment with the CPLEX v.12 solver.

The use of algebraic modelling language in GAMS facilitates the programming of optimisation problems close to their mathematical formulations with flexible and fast modifications. The separation of modelling platform and various solvers is another advantage of this software. Indeed, GAMS users can benefit update from hardware/operating system and the solver side for the problems of large sizes. It allows the access of the optimisation problems into a large number of solvers and algorithms without reformulation in different modelling languages in function of the model types (linear, nonlinear, integer, mixed). More than 25 solvers including commercial solvers are proposed on GAMS, in which for LP/MILP problems there are these solvers: BARON, BDMLP, CBC, CONOPT, CPLEX, LINDO, DECIS, GUROBI, GUSS, IPOPT, KESTREL, KNITRO, LGO, LINDOGLOBAL, LOCALSOLVER, MINOS, MOSEK, SNOPT, XA , XPRESS. Besides the large range of solvers, GAMS offers the important flexibility for modelling and optimisation on allowing the easy exchange data in the model through GAMS Data eXchange (GDX) file format, as well as development of the model whatever platform (Windows, Linus, Mac OSX, SOLARIS, Sparc Solaris, and IBM POWER AIX) or User Interface with the GAMS object-oriented APIs. Moreover, GAMS has links to applications like MS Excel, Matlab or R to create the productive tool environment for users.

For optimisation of LP and MILP problems, the most popular and well-known commercial software are among CPLEX, Xpress and Gurobi (Mansini et al., 2015). CPLEX named after the simplex method, implemented in the C programming language can now support other types of mathematical optimisation and offers interface other than C, including GAMS. In this study, the CPLEX 12 solver is used to resolve the LP and MILP problems. Moreover, this study can get the expertise of LGC in GAMS and CPLEX from various research projects (Boix, 2011; De León Almaraz, 2014; Ramos, 2016).

2.5.2. MCDM Software

Due to the hard pairwise comparisons from large range of solutions, Visual PROMETHEE v.1.4 (non-profit academic version) is applied to automate the ranking process. This software offers a friendly interface to input data, impose the criteria weight, analyse the preference degrees of the solutions and establish the sensitivity study with numerous visual tools. Indeed, it allows decision-makers focus on selection of the relevant solution and study of the impacts of criteria weights without taking much time in developing mathematical framework of this method.

2.5.3. Life Cycle Assessment

The environmental assessment is based on elementary environmental impacts coupled with the LCA software SimaPro 7.3. The ReCiPe Midpoint (H) v.1.06 method is adopted to evaluate GWP impacts for modelling and optimisation phases. This assessment method and the GWP indicator are used to be compatible for the exchanges in SEARRCH project among the partners.

2.5.4. Geographic Information System (GIS)

It is difficult to present the network configuration of the compromise solution obtained from optimisation due to the large spatial data (wastes sources, locations of recycling plants, distributions of wastes in different techniques, availability of recovered products, etc.). Therefore, a coupling of Google Maps and QGIS v. 2.8.3-Wien (Quantum Geographic Information System) is adopted to map the modelled system and the optimised results.

Google Maps is easy to collect geographic data with its large database while QGIS is a free, open-source and high-advanced GIS program which provides easy organisation, visualisation and analysis of spatial data. QGIS supports various data formats, such as ESRI shapefile, Mapinfo, CSV, PostGIS, KML, etc.

which allows the active data exchanges with other GIS tools (ArcGIS, Mapinfo, Google Earth, etc.) in QGIS. Furthermore, the development of numerous plug-ins in QGIS expand its core functionality.

2.6. Conclusions

The framework of methodologies used in this study can be visualised in Figure 2-4:

1. Development of mathematical model: this step involves of Data Collection and Mathematical Modelling which are actively interconnected in function of data availability and model complexity, e.g. time planning, geographic boundary, variation of techniques/wastes, performance indicators/criterion, etc. The economic data is based on literature while the majority of environment data is extracted by Life Cycle Assessment with Simapro. The spatial data of the case studies (locations, transport distances, map) come from GIS databases/tools, i.e. Google Maps, IGN (Institut National de l'Information Géographique et Forestière, www.ign.fr). Mathematical Modelling is carried out in GAMS interface.

2. The design of Pareto front of bi-criteria optimisation problem is carried out with lexicographic and ε-constraint methods. These methods generate respectively the optimum of each criterion (lexicographic) and the local optimum of every interval in Pareto front (ε-constraint) which is all determined by CPLEX solver in GAMS.

3. The determination of the compromise solution uses M-TOPSIS for bi-criteria optimisation (minimisation of cost and GWP (Chapter 4, Chapter 5); maximisation of NPV and minimisation of GWP (Chapter 5)). PROMETHEE is used to propose a relevant strategy for the three criteria, i.e. minimisation of recycled carbon fibre, maximisation of NPV and minimisation of GWP. The network configuration of the compromise solution is analysed by QGIS.

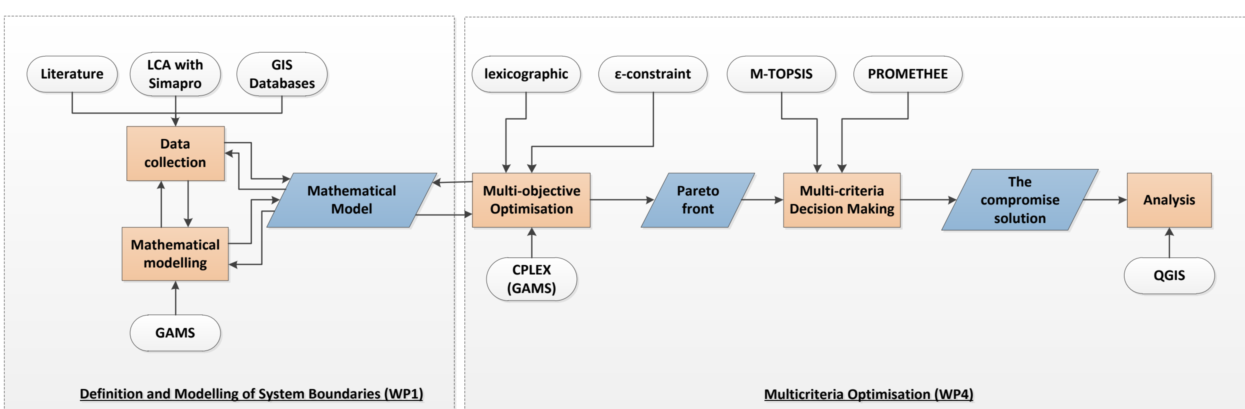


Figure 2-4: Methodological framework in this study

CHAPTER 3

Economic and Environmental assessment of Recovery and Disposal pathways for CFRP Waste Management

Abstract

This work is focused on the economic and environmental assessment of several composite waste treatment technologies to study the potential impacts of each pathway in CFRP waste management. Various indicators are used to represent the different viewpoints of the stakeholders involved in CFRP waste management. With their low treatment cost (0.1 €/kg), landfill and incineration still constitute the cheapest solutions for waste owners to remove their wastes in the absence of current strict regulations. For recyclers, recycled carbon fibres can substitute different grades of carbon fibres and glass fibres with competitive prices ranging from 0.25 €/kg to 4.5 €/kg with a panel of recycling techniques. GWP assessment promotes recycling activities by recovery of carbon fibre due to the high avoided impacts from substitution of virgin fibre, thus highlighting the high interest of recycling over conventional production for environmental purpose. Fibre recovery rate and recycling capacity are important factors to decrease the unity cost of recycled fibre as well as GWP impacts. This study allows analysing the advantages and drawbacks of each technique with economic and environmental indicators, to better understand the network configuration that will be obtained after the optimisation process.

Résumé

Ce chapitre porte sur l’analyse économique et environnementale de plusieurs procédés de traitement des composites afin d’étudier les impacts potentiels de chaque voie de valorisation de déchets composites de type CFRP. Divers indicateurs sont utilisés pour représenter les différents points de vue des parties prenantes impliquées par la gestion des déchets de CFRP. Avec un faible coût de traitement (0,1 €/kg), l'enfouissement et l'incinération sont toujours les solutions les moins coûteuses pour les propriétaires de déchets en vue de les éliminer en l’absence de réglementation stricte dans le domaine. Pour les recycleurs, les fibres de carbone recyclées peuvent remplacer différentes qualités de fibres de carbone et de fibres de verre à des prix compétitifs de 0,25 €/kg à 4,5 €/kg en mettant en jeu différents procédés de recyclage. L'évaluation du GWP favorise les activités de recyclage par récupération de la fibre de carbone en raison des impacts élevés évités par substitution de la fibre vierge, ce qui montre le fort intérêt du recyclage par rapport à production conventionnelle pour l'objectif environnemental. Le taux de récupération des fibres et la capacité de recyclage sont les facteurs importants pour diminuer le coût unitaire de la fibre recyclée et obtenir une réduction importante des impacts du GWP. Cette étude permet d'analyser les avantages et les inconvénients de chaque technique selon des indicateurs économiques et environnementaux, afin de mieux comprendre la configuration du réseau qui sera obtenue après la phase d'optimisation.

3.1. Introduction

The literature review shows the large availability of FRP/CFRP waste treatment techniques which may recycle carbon fibre into different forms and qualities or recover wastes on energy. The independent assessment of each pathway through its inputs and outputs under economic and environmental indicators is essential for system modelling in order to study its characteristics and determine its advantages and weaknesses before the optimisation process.

Composite waste treatment technologies that have been identified in the dedicated literature whatever their technology readiness level (TRL), i.e. landfill, incineration, co-incineration, mechanical recycling, pyrolysis, microwave and supercritical water, are all assessed in this chapter with economic and environmental indicators. In particular, the goal of this work is to study the potential impacts of each pathway in CFRP waste management considering both economic and environmental issues, which has not been studied in such an exhaustive and complementary way. The study on different indicators which represent various viewpoints of stakeholders is also discussed for enhancement of recycling CFRP against the non-recovery pathways.

Otherwise, the innovative part of this part is to constitute the basis for the development of a methodological framework for the design and deployment of CFRP waste supply chain and to highlight the endogenous variables including the characteristics of each waste treatment option as well as the exogenous ones (type of CFRP waste, deposit waste, transport distance, market) which will be studied by optimisation stage in the two next chapters.

The framework for CFRP waste management and the methodology for economic and environmental assessment will be addressed in Section 3.2. The model development for each waste treatment technique including data input and the assumptions used are also detailed in this section. The analysis and the results are presented in detail in section 3.3. Finally, Section 3.4 will conclude this study on CFRP waste management and offer perspective for CFRP waste supply chain deployment and optimisation.

3.2. Materials and Methods

3.2.1. Studied System

The system boundary considered is presented in Figure 3-1. All the impacts or benefits are assessed from the beginning to the end of operation leading to different recovered products until there is no waste left to be treated. Two options concerning carbon fibre recovery are considered: Recovery Pathways and Non-Recovery Pathways. The techniques in the former category allow recycling carbon fibre. In the latter one, although carbon fibre cannot be directly recycled, either energy or materials recovery may be obtained by incineration or co-incineration techniques. All the studied techniques will be presented in detail in Section 3.2.3.

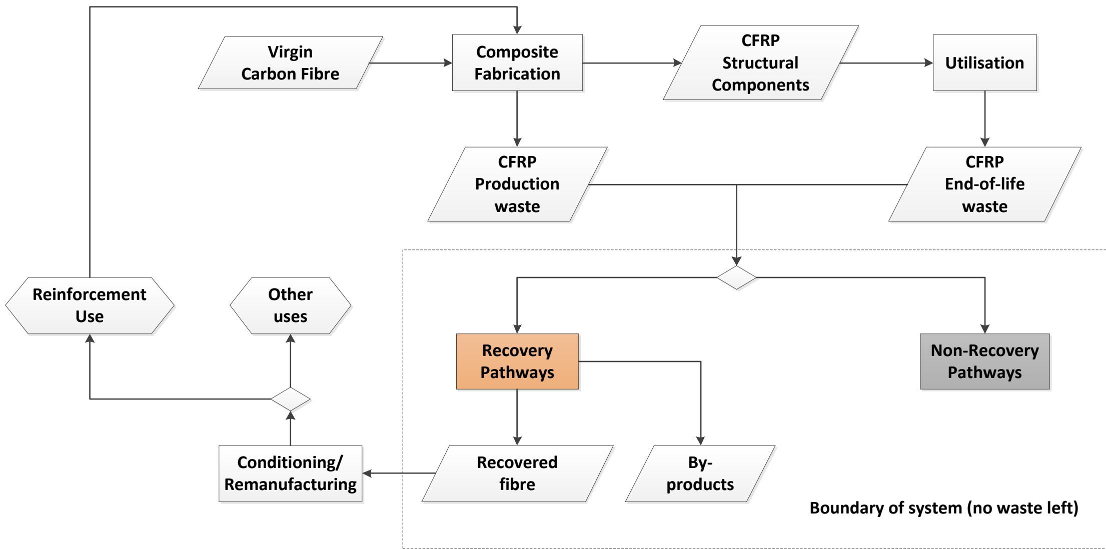


Figure 3-1: Boundary of the studied system

An average composite waste of CFRP type composed of 65 wt% of carbon fibre and 35 wt% of matrix has been considered. The studied carbon fibre is assumed to be produced from PAN precursor. The formulation of the composite will not be further developed and 100 % of matrix is assumed to be composed by Bisphenol A epoxy resin without filler.

As CFRP is the composite of polymer matrix, it is not classified as an inert waste regarding organic substances for matrix. In waste management, CFRP can be considered as either non-hazardous waste or hazardous waste depending on matrix properties. Prepreg, which is an uncured composite, is considered as a hazardous waste because of the risk phases of uncured polymer matrix (PlasticsEurope, 2006). The cured composite is considered as a non-hazardous waste if it does not involve any hazardous substance in its formulation.

3.2.2. Assessment methods

Since the products from the studied waste treatment techniques are different in both type and yield, the functional unit (FU) defined for this study is 1 kg of waste to be treated by one of the proposed technology. Within the boundary of the studied system, three phases of CFRP waste management are assessed: plant construction, operation, and applications for recovered products. These three steps are studied complementally through economic assessment and environmental assessment.

3.2.2.1. Economic Assessment

According to literature, composite recycling suffers from financial instability due to the low value of recovered products and the lack of market (Yang et al., 2012). In this context, the aim of is here to develop an economic model of CFRP waste management in order to study the profitability of recycling techniques. A multi-period of 10 years is considered to study the economic feasibility of the project.

It must be emphasized that the cost of CFRP waste has been set equal at zero even though it can be considered as a raw material. Even if this assumption cannot be viewed as a penalizing one as it is generally recommended at earlier design step, it can be justified here in order to promote the deployment of the market of the recycled fibre.

- The **Non-Recovery Pathways** are considered as outsourcing services of the system, their costs are therefore estimated on the basis of the current fees charged by the government or the concerned industry.

- For **Recovery Pathways**, the contribution of variable costs, fixed capital costs and capital depreciation has been determined using classical methodologies for early estimates as reported in (Anderson, 2009) (see Table 3-1). A linear 10 year-depreciation is considered. The investment cost is estimated from the classical six-tenths rule for a fixed capacity of waste input (Seider et al., 2009) . The utility costs including electricity, natural gas, and water have been extrapolated from literature data. The requirement of utilities depends on the recycling techniques that will be presented in the next section. For labour cost, the legal working hours of 1,607 hours per year with an hourly cost of 34.3 € (Eurostat, 2015a) have been considered. In this study, the recycling plants are assumed to be medium scale with 4 people for operating labour. This assumption will be valid for all recycling plants whatever the process and the capacity used.

Table 3-1: Framework of economic model for Recovery Pathways

Cost (€/year)	
Depreciation (D)	Investment/(number of years of the project) (*)In this study, the life span of project is 10 years
Raw Material Cost ($Cost_1$)	Excluded (the cost of waste is assumed to be zero)
Utility Cost ($Cost_2$)	Function of techniques
Operating Labour Cost ($Cost_3$)	4 operating personnel
Maintenance Cost ($Cost_4$)	0.02 x Investment
Supplies ($Cost_5$)	0.3 x Operating Labour Cost
Administration ($Cost_6$)	0.9 x Operating Labour Cost
Non-Operating Labour Cost ($Cost_7$)	0.6 x Operating Labour Cost
Others cost ($Cost_8$)	0.01x Investment

Three economic indicators are considered in this study (Table 3-2).

1. Operation Cost per mass unit of waste (OC) is the cost of input utilities required by each recycling technique.

2. Average Unit Cost per mass unit of waste (UCW): for Non-Recovery techniques, this indicator corresponds to the total fees charged by government or the concerned industry; for Recovery pathways, this indicator is the breakeven point charged to an amount of waste through a 10-year horizon time of recycling plant for Recovery pathways. It corresponds classically to a zero value of NPV of the project calculated by equation (3.1).

3. Average Unit Cost per mass unit of recovered fibre (UCF) is computed similarly on a different basis. It only concerns Recovery Pathways, which is the average cost of recovered fibre during 10-year horizon time so that recycling plants can cover all their manufacturing cost and begin to have profit.

In this assessment, the profit from by-products (filler, oligomers) is not considered in total revenue to estimate the values of UCW and UCF of Recovery pathways to avoid the interference on fibre recycling. With the core of recycling activity, different economic viewpoints are studied through these two indicators from waste owners with UCW and clients of recycled fibre with UCF.

Table 3-2: Formula for economic indicators

Indicator	Formula	
	Non-Recovery Pathways	Recovery Pathways
Operation Cost per mass unit of waste (OC)	_	Utilities Costs
Average Unit Cost per mass unit of waste (UCW)	Fees (charged by government or industry)	$\frac{\text{REV (at NPV} = 0)}{\text{Waste input capacity}}$
Average Unit Cost per mass unit of recovered fibre (UCF)	_	$\frac{\text{REV (at NPV} = 0) - \sum \text{Revenue of other products}}{\text{Recovered fibre capacity}}$

$$NPV = -INV + \sum_{t=1}^{10} \frac{(REV - TC) \times (1-a) + D}{(1+\beta)^t} \qquad (3.1)$$

with H: the horizon time of recycling plant (10 years)

t: the year index

a: tax rate (34 %)

β: discount rate (10 %)

INV: Investment cost

REV: Annual Revenue of process

D: Depreciation ($D = \frac{INV}{H}$)

TC: Total annual costs ($TC = D + \sum_{i=1}^{8} Cost_i$)

3.2.2.2. Environmental Assessment

Besides the impacts released from operation's activities, the impacts related to plant construction have been considered as insignificant compared to the operating phase: this assumption has been considered for valid for a lot of chemical processes (Morales Mendoza, 2013). The benefits obtained from recovered products have of course been included in environmental assessment with the avoided impacts. Three indicators involving GWP are computed:

1. GWP impact of process (GWPP) encompasses all the activities of waste management

2. GWP impact of substituted products (GWPA) includes the GWP impacts from the utilisation of recovered products to replace virgin materials. In this study, a quantity of recovered products is assumed to replace the equivalent quantity of virgin materials (1:1 ratio). This assumption is proposed in order not to limit the applications of recovered fibre by mechanical properties as proposed in (Witik et al., 2013). The GWPA for an amount of recovered products is therefore equal to GWP impacts of production of the same quantity of virgin products which the recovered products replace;

3. Finally, GWP total of the system (GWPTOT) which take into account impacts from both activities and substitution effect: $GWPTOT = GWPP - GWPA$

3.2.3. Input Data

All the studied technologies are assumed to be available to treat CFRP waste. The mass and energy balances of each pathway in the modelled system are summarised in Figure 3-2. The data used in economic assessment and environmental assessment can be found in Table 3-3 and Table 3-4. The typical features of each pathway will be shortly presented together with the analysis.

3.2.3.1. Non-Recovery Pathways

a. Landfill

Landfill can be defined as a specific underground storage of waste when there is no available recycling technique for this kind of waste. In this study, landfilling is considered as a disposal pathway, not as a kind of storage. Therefore, once landfilled, the potential recovered products from waste are lost. The composite waste that is likely to be landfilled is considered as non-hazardous solid waste on considering the assumption of CFRP waste type.

No specific process for composite landfilling is defined in Simapro v.7.3 databases, e.g. Ecoinvent 2.2. The landfilling of plastics mixture in sanitary landfill process, which is the closest option to composite landfilling solutions regarding the similar organic chemical nature of polymeric composite and plastics, has been adopted in order to evaluate GWPP of CFRP waste landfilling. The impacts from losing the recyclable fibre in CFRP waste are considered in order to avoid neglecting the lost potential in landfilling. These lost impacts are evaluated at negative GWPA of production for the equivalent quantity of virgin carbon fibre as the quantity of carbon fibre presented in landfilled CFRP waste.

According to (GPIC et al., 2003), the fees of composite landfill is around 76 to 90 €/tonne. In another report in 2012 by (Fischer et al., 2012) for EEA, the general landfill charge in France in 2015 is estimated of 95€/tonne. This value is used in this study for economic assessment.

b. Incineration

Incineration is a thermal process, which allows recovering energy in heat resulting of waste combustion. The heat can be used directly or converted into electricity. In this scenario, the process is assumed to be auto-thermal; the heat and the ash by-product released from the process are estimated 32 MJ and 8 wt% of input waste respectively like the work of (Witik et al., 2013) the emission of combustion is based on the test presented in (Hedlund-Åström, 2005). The heat is then converted to electricity with an efficiency of 35 % (Antonini, 2012). The ash by-product is landfilled as an inert waste. The cost of general waste incineration is about 92 €/tonne in France in 2015 according to (Fischer et al., 2012). The UCW of this route includes this charge and the cost of ash landfilling.

c. Co-incineration

As incineration and co-incineration are both based on combustion of waste, we assume that there is no change in the quantity of heat and ash produced in co-incineration compared with incineration technique. However, co-incineration allows material recovery in addition to energy recovery. Indeed, in co-incineration technique, waste is used as a substituted fuel involved in clinker fabrication where coal is normally used as a fuel and the products of waste combustion, i.e. heat and ash, are completely valorised in co-incineration. Heat released from combustion of CFRP waste can substitute the same amount of heat from coal combustion in furnace. Otherwise, ash is mixed with the raw materials of clinker in its manufacturing. According to (Halliwell, 2006), the cost of treatment of co-incineration of composite waste charged by the cement industry is around 1 € per kg. This cost is considered as UCW for this technique.

3.2.3.2. Recovery Pathways

The techniques that have been investigated here have been selected as they are representative of the existing processes: grinding, pyrolysis, microwave, and supercritical water (SCW). These techniques have attracted a lot of attention from academic and industry and have reached at certain maturity of development. Grinding process is the simplest recycling technique with only energy requirement but the recovered products cannot be used in high-valued applications due to strong degradation of recovered fibre and unclear separation of fibre-matrix. Pyrolysis is the most successful industrialised technique which allows recycling CF cleanly with high retention of mechanical properties but it requires high energy consumption. Another thermal technique, microwave can recycle CF with less energy than pyrolysis and lead to potential recovery of matrix. SCW is the recycling technique in trend because of the utilisation of water, a cheap and low-hazardous risk raw material compared with organic solvents, but this technique requires high energy to operate at supercritical conditions.

Although recycling yield of carbon fibre in CFRP waste has not reached 100 %, the recent results obtained are promising (Oliveux et al., 2015a). In this study, we consider that CF can be ideally recycled at 100 % yield by pyrolysis, microwave and SCW to study the maximum benefit that can be potentially obtained without introducing a bias in the analysis since the recycling yield of CF may vary in different works.

For CFRP based on bisphenol A epoxy resin, the residuals are constituted of phenol derivatives principally. Due to the complexity of oligomers mixture, the residuals from decomposition of matrix are simplified to be reused as phenol in this study.

Technical, economic and environmental data have been collected regarding CFRP applications. Yet, in case of lack of data, those relative to GFRP will be used. The majority of recycling techniques on fibre recovery from FRP waste have been developed for both GFRP and CFRP because of the similarity of these two polymeric composites, e.g. (Kennerley et al., 1998; Pickering et al., 2000; Yip et al., 2001; Jiang et al., 2008) for fluidised bed, or (Lester et al., 2004; Akesson et al., 2013; Obunai et al., 2015) for microwave, etc. Based on reviews in composite recycling, the capacity of the plant of each technique is assumed to be set at 4000 tonnes/year for mechanical recycling, 2000 tonnes/year for thermal recycling (pyrolysis and microwave) and 1000 tonnes/year for chemical recycling (SCW), respectively.

a. Grinding

The principle of this technique is to separate fibres from matrix by a grinding process. After mechanical process and sieving, the obtained products are a mixture of matrix and fibre. They are separated into different fractions in function of the proportion and the length of fibre (Kouparitsas et al., 2002; Palmer et al., 2010).

From the work of (Palmer et al., 2009), two products are assumed to be recovered from the composite waste: a powder product (29 wt%), which is rich in matrix and used as filler, and a fibrous fraction (71 wt%), which is rich in fibre. The process energy of this technique is estimated at 0.27 MJ/kg by (Hedlund-Åström, 2005) which is in agreement with the value proposed by (Howarth et al., 2014) in a test with industrial equipment.

In this work, the mechanical technique is based on ERCOM process which operates at industrial scale by using a mobile shredder and hammer mill. The plant has a capacity of 4000 tonnes/year with a mobile shredder of value of 200 000 € (Halliwell, 2006). The capital cost of hammer mill is presented in detail and has been assumed to be one third of the value of shredder (Schutte Buffalo Hammermill).

b. Pyrolysis

In this study, the pyrolysis is modelled as a combustion process of the matrix (35wt% of CFRP waste) environmental impacts. No energy recovery from thermal decomposition of matrix has been assumed. The total energy used in pyrolysis has been estimated at about 30 MJ/kg composite (Witik et al., 2013).

Pyrolysis for composite recycling in general requires a minimum 10 million € for capacity 20,000 – 80,000 tonnes/year (Krawczak, 2012). The mean of this range (50,000 tonnes/year) has been assumed to have the same amount investment and then used to estimate the corresponding capital cost of the studied capacity by six-tenths rule.

c. Microwave

The process energy is estimated at 10 MJ/kg according to (Lester et al., 2004; Suzuki and Takahashi, 2005). According to (Lester et al., 2004), oligomers from decomposition of polymeric matrix can be obtained by this technique. In another study on GFRP of (Akesson et al., 2013), besides the recovery of solid product, i.e. glass fibre, the thermoset matrix (unsaturated polyester resin) is decomposed into pyrolysis oil and gas with 56 wt% and 44 wt% of quantity of matrix in waste respectively. These yields will be used to estimate the quantity of oligomers and the emission of CO_2 released from 35 wt% of matrix in the studied CFRP waste through this process. The pyrolysis oil, which is composed of various aromatic substances, is considered as phenol in this model. The gas fraction which is composed of a rich amount of CO and CO_2 with low presence of methane and other hydrocarbons reported in the study of (Akesson et al., 2013) is assumed to be exclusively composed of CO_2 considering a total oxidation.

No information of investment cost on FRP recycling is yet available. This later is estimated based on the BRC process for tyres scrap treatment (Appleton et al., 2005) which is estimated 9 400 000 £ for capacity of 50 000 tonnes/year. The investment cost of the BRC process reported in 1990s is updated from 1995 to 2014 by Chemical Engineering Plant Cost Index (CEPCI).

d. Supercritical water

In supercritical condition (temperature > 374 °C and pressure > 221 bar), “the properties of water change considerably: the hydrogen bonds disappear and water becomes similar to a moderately polar solvent; oxygen and all hydrocarbons become completely miscible with water; mass transfer occurs almost instantaneously; and solubility of inorganic salts drops to ppm range” (Liu and Lipták, 1999). Due to these properties, the polymer matrix is decomposed into different oligomers and the carbon fibre is recovered in supercritical water.

This technique has been industrialised for hazardous waste treatment since 1980s (Marrone, 2013). For composite application, although it has received a lot of attention from academics and industry (Oliveux et al., 2015a), supercritical water for CFRP waste is still at pilot scale. As information of this process is still limited, data used for assessment are based on the work of (Knight, 2013). For an amount of 1 kg of CFRP (35 wt% matrix) waste, the process requires 2.61 kWh of electricity, 1.64 m^3 of natural gas, 3.5 kg of pure water for solvent and 72.07 tonnes of cooling water. CFRP waste is assumed to be entirely recovered with 100 % yield of carbon fibre and matrix (in the form of oligomers). The capital cost of 5,770,000 $ for 150 kg/hour of capacity has been adopted from in (Knight, 2013) considering an investment cost of a 1000 tonnes/year plant for a recent developed technique.

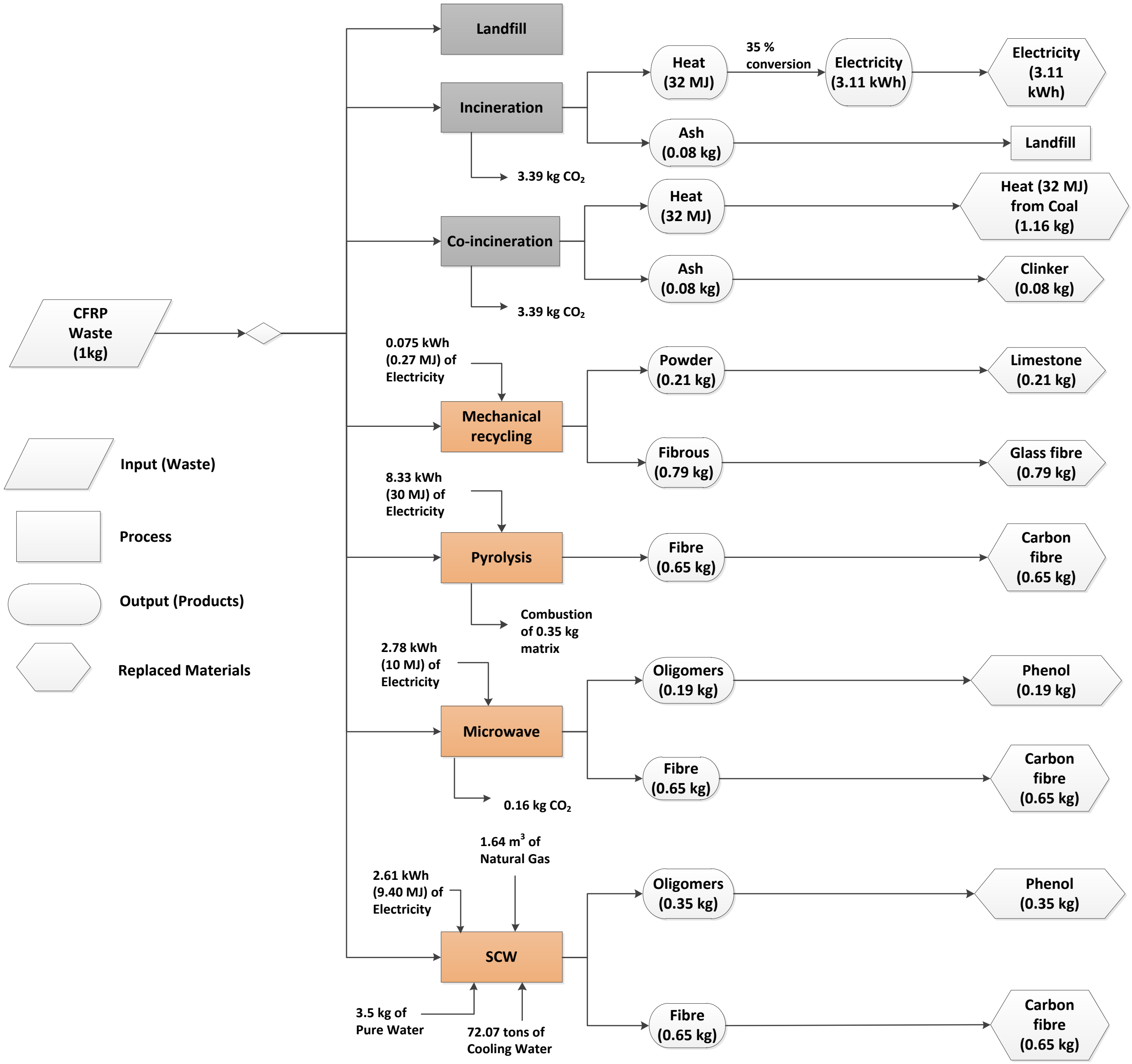


Figure 3-2: Materials flows in the studied system (Hedlund-Åström, 2005; Suzuki and Takahashi, 2005; Palmer et al., 2010; Akesson et al., 2013; Knight, 2013; Witik et al., 2013; Howarth et al., 2014)

Table 3-3: Data of Unit Cost and GWP impact in the modelled system

Material/Activity	Unit Cost	GWP impact
Input Electricity	0.091 €/kWh (Eurostat, 2015b)	0.0262 kg CO_2 eq./MJ (Electricity, medium voltage, at grid/FR – Ecoinvent v2.2/ ReCiPe Midpoint (H) v.1.06)
Input Natural Gas	0.16 €/m^3 (Knight, 2013)	0.38 kg CO_2 eq./m^3 (Natural gas, at long-distance pipeline/RER – Ecoinvent v2.2/ ReCiPe Midpoint (H) v.1.06)
Input Pure Water	2.20 €/tonne (Knight, 2013)	0.000679 kg CO_2 eq./kg (Water, ultrapure, at plant/GLO – Ecoinvent v2.2/ ReCiPe Midpoint (H) v.1.06)
Input Cooling Water	13.27 €/1000 m^3 (Knight, 2013)	0
Limestone	90.91 €/tonne (ICIS, www.icis.com)	0.0132 kg CO_2 eq./kg (Limestone, milled, loose, at plant/CH U – Ecoinvent v2.2/ ReCiPe Midpoint (H) v.1.06)
Clinker	/	0.901 kg CO_2 eq./kg (Clinker, at plant/CH – Ecoinvent v2.2/ ReCiPe Midpoint (H) v.1.06)
Heat from coal	/	0.131 kg CO_2/MJ (Heat, at hard coal, burned industrial furnace, 1-10MW/MJ/RER – Ecoinvent v2.2/ ReCiPe Midpoint (H) v.1.06)
Electricity (valorised from heat in incineration)	/	0.0256 kg CO_2 eq./MJ (Electricity, medium voltage, production FR, at grid/FR – Ecoinvent v2.2/ ReCiPe Midpoint (H) v.1.06)
Virgin ex-PAN Carbon Fibre	/	31 kg CO_2 eq./kg (Das, 2011)
Virgin Glass Fibre	1-30 €/kg (Dupupet, 2008)	2.6 kg CO_2/kg (Kellenberger et al., 2007)
Recycled Glass fibre	0.25 €/kg (Job, 2013)	/
Oligomers	1.52 €/kg (ICIS, www.icis.com)	3.86 kg CO_2/kg (Phenol, at plant/RER – Ecoinvent v2.2/ ReCiPe Midpoint (H) v.1.06)
CFRP waste landfilling	95 €/tonne (Fischer et al., 2012)	0.0897 kg CO_2 eq./kg (Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH – Ecoinvent v2.2/ ReCiPe Midpoint (H) v.1.06)
Ash landfilling (in incineration)	95 €/tonne (Fischer et al., 2012)	0.0122 kg CO_2 eq./kg (Disposal, inert material, 0% water, to sanitary landfill/CH – Ecoinvent v2.2/ ReCiPe Midpoint (H) v.1.06)
Matrix combustion (in pyrolysis)	/	2.35 kg CO_2 eq./kg (Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH – Ecoinvent v2.2/ ReCiPe Midpoint (H) v.1.06)

Table 3-4: Data of Investment Cost for Recovery Pathways

Technique	Investment Cost for Process in literature	CAPEX used in Economic Assessment
Grinding	200 000 € for a shredder of capacity of 4000 tonnes/year (Halliwell, 2006)	265 000 € of capacity of 4000 tonnes/year
Pyrolysis	10 000 000 € for capacity of 20 000-80 000 tonnes/year (Krawczak, 2012)	1 450 000 € of capacity of 2000 tonnes/year
Microwave	9 400 000 £ for capacity of 50 000 tonnes/year (tyres application) (Appleton et al., 2005)	2 550 000 € of capacity of 2000 tonnes/year
Supercritical water	5 770 000 $ for capacity of 150 kg/hour (Knight, 2013)	6 430 000 € of capacity of 1000 tonnes/year

3.3. Results and Discussion

The two first sections address the economic and environmental assessment of the studied CFRP waste treatment techniques. The advantages and the limitations of the indicators used in the analysis of CFRP waste management will be also discussed. The sensitivity study of Recovery Pathways on recycling capacity and CF recovery rate will be presented in the third section.

3.3.1. Economic Assessment

Figure 3-3 presents the values of OC, UCW and UCF for all the studied CFRP waste techniques. Based on UCW indicator, it must be first emphasized that not surprisingly, the fibre recycling techniques are not interesting solutions compared to the cost of landfill and incineration. These options (requiring around 0.1 €/kg of waste) are the most competitive ones for CFRP waste treatment without consideration of profits from recoverable products in waste. This indicator may reflect the viewpoint of the waste producer who will be referred as the « waste owner » who may have no economic interest to reuse or stock waste and have to select one of the existing techniques in order to remove waste at minimal cost. So, this may suggest that if no regulation is imposed, landfill and incineration will continue to be the dominant economic choice in CFRP waste management at current costs despite there is no mass recovery in these options.

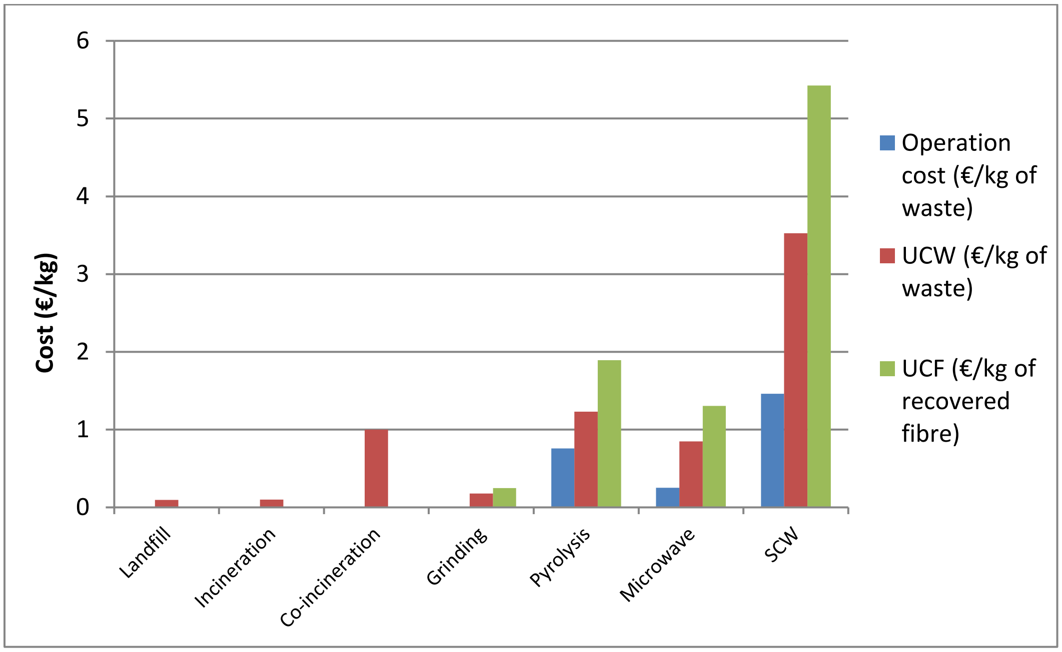


Figure 3-3: Economic assessment of the studied pathways

Although it cannot recycle carbon fibre, co-incineration allows valorising entire waste on both energy and material aspects, and avoids an amount of coal and raw materials in clinker production. With a charge of 1€/kg of waste by cement industry, co-incineration loses its economic interest compared to landfill or incineration and even to other fibre recycling techniques like grinding and microwave, despite its advantage on waste valorisation. However, if this technique is charged at the same fee of incineration, it is more interesting than incineration and landfill because this technique allows reducing the cost of ash landfilling in incineration by material recovery in clinker fabrication. However, the choice of non-recovery techniques is temporary and depends largely on the acceptance of recycled carbon fibre in market. When the profit of RCF becomes interesting, the non-recovery pathways will become obsolete for CFRP waste management.

Operating with low energy consumption, grinding has the lowest value in Operation Cost in the Recovery pathways. Although the UCW of this technique is little higher than the cost of landfill and incineration, it is the cheapest one compared to the value of UCW for the three other recycling techniques due to simple equipment and high capacity. Pyrolysis and SCW which operate at high temperature or high pressure, exhibit a high Operation Cost. This factor has an influence on the UCW indicator relative to these techniques, especially in SCW technique. It can clearly be observed that SCW leads to both the highest Operation Cost and UCW because of the conjunction of three factors, i.e., high utility cost, high investment and small capacity. Operating at the same capacity (2000 tonnes/year), microwave is more interesting than conventional pyrolysis regarding its lower Operation Cost and UCW principally due to energy reduction in microwave heating which requires only one third of energy used in pyrolysis. With UCW varying from 0.18 to 3.53 €/kg of waste, the Recovery Pathways cannot compete with the Non-Recovery Pathways if there is neither market for recovered fibres nor regulation constraints.

In this context, UCF indicator is used to study the acceptable price range at which recovered fibres can be sold as well as their potential applications that can be determined in order to promote recycling and markets of recovered fibre. For this purpose, the UCF of recovered fibre from the Recovery Pathways will be compared with the average price of virgin carbon fibre, virgin glass fibre and recovered glass fibre in current market. This evaluation is essential to study possibility of utilisation of recovered fibre in classical applications of virgin carbon fibre (VCF) or virgin and recycled glass fibre by an economic viewpoint. The price of VCF may vary according to different grades on mechanical properties, precursors and production technique, etc…. from a price less than 20 $/kg (low modulus) up to 2000 $/kg (ultra-high modulus) (Chen, 2014). In a context where carbon fibre will be popularised in wide applications such as automotive, the production of carbon fibre from cheap precursor like lignin can reduce the manufacturing cost of CF at around 6.6 $/kg (5.92 €/kg). According to (Berreur et al., 2002), the ideal prices of carbon fibre are estimated about 4.5-7.5 €/kg. Besides, the price of glass fibre is much lower than that of carbon fibre. The price of glass fibre is estimated at 1-3 €/kg for general purpose and 3-30 €/kg for high technology applications (Dupupet, 2008), while recovered glass fibre is sold at 0.25 €/kg (Job, 2013).

UCF for grinding (evaluated at 0.248 €/kg) exhibits a value that is very similar to the price of recovered glass fibre. The value of UCF for recovered fibre from thermal techniques is higher than the minimum price of virgin glass fibre (1 €/kg), but remains lower than the lowest price (i.e. 4.5 €/kg) of carbon fibre that is used for general applications (Berreur et al., 2002). Based on the assumptions of this study, the UCF of SCW is estimated at 5.43 €/kg which is the highest cost among the Recovery pathways and exceeds the threshold of 4.5 €/kg for carbon fibre price. Mechanical recycling has the least UCF cost, but carbon fibre cannot be cleanly separated from the matrix and the recovered products are usually used in low value applications. Although SCW has the highest UCF, the recovered fibres by this technique have the tensile strength which is slightly near the one of virgin fibres (Table 1-6). This technique needs yet improvement to reduce investment cost and an expansion of capacity is required so that this process becomes more competitive than other recycling techniques such as pyrolysis or microwave.

The UCF value estimated in this study is yet lower than the data reported by (Oliveux et al., 2015a) in which 13 – 19 $/kg for RCF from thermo-chemical recycling and 5 $/kg (3.36 €/kg) for ground CFRP. The gap can be explained by several factors: (i) the studied system does not consider exogenous factors (type of CFRP waste, transportation, conditioning process, packaging, etc.); (ii) average data and fixed capacity are used. However, the reported cost of recycled carbon fibre seems less attractive compared to the price of virgin carbon fibre by cheap precursors like lignin (6.6 $/kg,(Chen, 2014)). It must be emphasized that, the recycled fibre costs have two competitors according to the targeted market: for low value use in which the price of recycled fibre must be extremely competitive; whereas for high-value applications, they have to compete with virgin fibres in which the economic aspect is not priority but the quality of carbon fibre (see Table 3-5). That makes recovered fibre more difficult to overcome virgin fibre.

Table 3-5: Price ranges of carbon fibres and glass fibres in market

Type of Fibre	Prices
Virgin conventional CF (low modulus)	< 20 $/kg (Chen, 2014)
Virgin conventional CF (standard modulus)	20 – 55 $/kg (Chen, 2014)
Virgin conventional CF (intermediate modulus)	55 – 65 $/kg (Chen, 2014)
Virgin conventional CF (high modulus)	65 – 90 $/kg (Chen, 2014)
Virgin conventional CF (ultra-high modulus)	up to 2000 $/kg (Chen, 2014)
Low-cost CF	4.5-7.5 €/kg (Berreur et al., 2002)
Virgin CF (from lignin precursor)	6.6 $/kg (Chen, 2014)
Recycled CF (from Thermo-Chemical recycling)	13 – 19 $/kg (Oliveux et al., 2015a)
Ground CFRC	5 $/kg (Oliveux et al., 2015a)
Virgin GF (for general purpose)	1-3 €/kg (Dupupet, 2008)
Virgin GF (for high technology applications)	3-30 €/kg (Dupupet, 2008)
Recycled GF	0.25 €/kg (Job, 2013)

Finally, it must be said that although the economic benefit that may result from the by-product release for some specific markets is not considered, the associated environmental benefit is taken into account via the concept of avoided impacts. The key factors from this economic assessment include recycling capacity and carbon fibre recovery that will be assessed in the sensitivity study section.

3.3.2. Environment Assessment

Three indicators for the evaluation of GWP impacts are used in this assessment: GWPP, GWPA and GWPTOT (see Section 3.2). The obtained results are displayed in Figure 3-4.

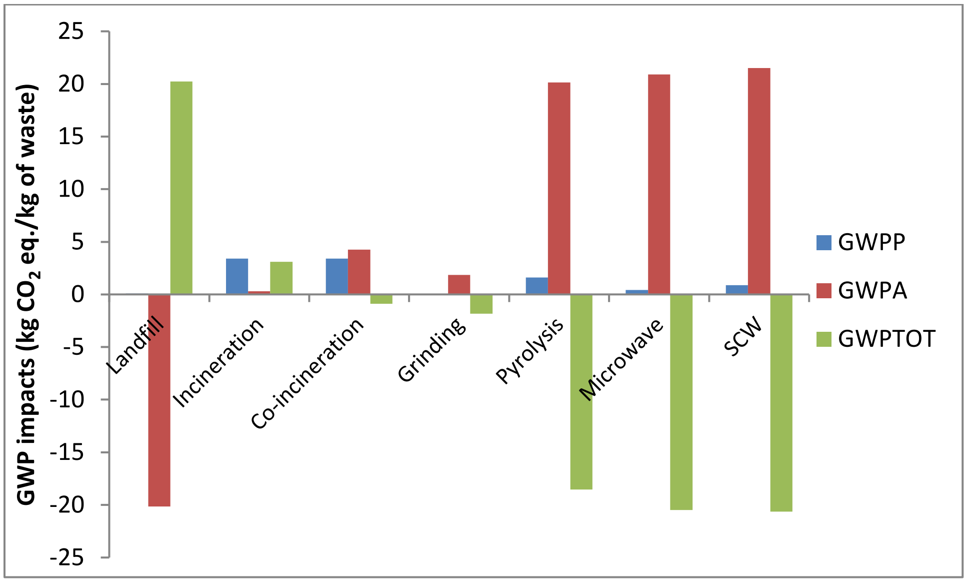


Figure 3-4: Environment assessment of the CFRP waste treatment techniques

The thermal techniques, i.e. pyrolysis, co-incineration and incineration are the pathways that exhibit the highest values for GWPP impacts. The combustion in pyrolysis involves the decomposition of the polymeric part, so that a lower GWPP impact is released than the one resulting from the combustion of the entire composite in incineration and co-incineration. Co-incineration induces slightly lower impacts than incineration because it does not need ash landfilling like incineration. For the other techniques with no or very low GHG emissions, the GWPP impacts depend majorly on the consumption of utilities in the process. Concerning GWPP impacts, the processes can be ranked in increasing order, that is, mechanical recycling, landfill, microwave, SCW. Although microwave and pyrolysis belong to thermal recycling, the recovery of oligomers from matrix in microwave reduces the GWP impacts compared to pyrolysis by avoiding the combustion of the entire matrix.

GWPA assessment is essential to study the outcome of waste treatment activities. If only the GWP impacts of the activities are assessed in the system, the potential benefit from materials recovery by recycling techniques or the loss of materials in landfill can be under-evaluated. The materials that can be replaced by the recovered products that can be generated by each technique are presented in detail in Figure 3-2. Despite its low GWPP impacts, landfill has high GWPTOT impacts since landfilling activity loses the recycling potential of carbon fibre in CFRP waste. In spite of a higher UCW cost, the interest of co-incineration over incineration is shown through GWPA evaluation. The benefit from recovery of entire CFRP waste on energy and material in co-incineration allows compensating over the GWP impacts produced in the process (GWPP), so that GWPTOT impacts become negative. Yet due to the specific situation of France that is explored in the study, the heat recovery from electricity conversion in incineration is not very profitable towards GWP impacts: the avoided impacts are too low to compensate all GWPP of this technique since the GWPA impacts of incineration are evaluated from GWP of mix electricity in France which is produced principally from nuclear power (75 %) and others (hydropower – 12 %, hard coal – 4 %, natural gas – 4 % and imported – 2%) (Itten et al., 2012).

The GWPA evaluation of recycling techniques depends strongly on replaced materials. The production of VCF is extremely energetic and emits much higher GHG than the production of glass fibre or the other recovered products (limestone, phenol). Therefore, the avoided impacts from replacement of VCF by RCF contribute an important contribution of GWPTOT for the studied techniques, which recycle carbon fibre cleanly such as pyrolysis, microwave and supercritical water. The effect of the low-value applications of recovered products from mechanical recycling (glass fibre and limestone) is indeed recognised in the GWPA assessment. This technique is the least interesting options among the recycling pathways despite its low GWPP impacts. The recovery of by-products apart from carbon fibre in microwave and supercritical water produces more advantages for these techniques than pyrolysis. However, another option of pyrolysis process equipped with a section for recovery of condensable decomposed polymeric matrix from the incomplete oxidation may exhibit similar GWPTOT performances with microwave and supercritical water.

For all the studied recycling techniques, the GWPP impact is low enough so that the avoided impact from the recovered products compensates all the GWPP impacts and GWPTOT is negative. GWPA impact assessment promotes the implementation of recovery pathways while the market of recycled carbon fibre has not been mature yet.

To evaluate the potential benefit of recovered products, all the studied indicators, i.e., GWPA GWPP, UCW and UCF are complementary in the study of entire CFRP recycling system from plant deployment to waste recovery.

3.3.3. Sensitivity analysis

The sensitivity study is aimed to assess the effect of the key factors for recovery pathways. The first part will be focused on recycling capacity and the data uncertainty used in economic assessment. The second part is dedicated to the influence of the material type replaced by recovered fibre through the variation of UCF and GWPTOT of the recycling techniques in function of carbon fibre recovery rate.

3.3.3.1. Capacity of recycling techniques

The economic assessment has highlighted that UCF depends on the installed capacity of the recycling techniques: UCF varies in function of capacity due to waste quantity input and the capital cost. This study is aimed to analyse the impact of this factor on UCF of each technique. Three levels of recycling capacity have been selected, i.e., 1000, 2000 and 4000 tonnes/year that correspond to small, medium and large range of FRP recycling industry.

The increase in recycling capacity reduces not surprisingly the UCF of recovered fibre (Figure 3-5). The UCF of grinding for three scales (lower than the UCF of other techniques) are all lower than 1 €/kg and even down to 0.25 €/kg. This result promotes the use of grinding in the classical applications of glass fibres, even in the lowest grade (recovered glass fibre) with the threshold of 0.25 €/kg. However, the UCF values for pyrolysis, microwave and SCW are all higher than 0.25 €/kg. The recovered fibre from these techniques cannot be reused in the same grade as recycled glass fibre. For the recovered fibre from pyrolysis and microwave, the application range may include at least the substitution of the general purpose grade of glass fibre with their UCF range from 1.6 – 2.4 €/kg (pyrolysis) and 1 – 1.9 €/kg (microwave). With the capacity of 1000 – 4000 tonnes/year, the range of UCF of SCW is around of 1 – 3 €/kg of general purpose glass fibres. The UCF value are 5.4, 4.4 and 3.8 €/kg for 1000, 2000 and 4000 tonnes/year respectively which are lower than the price of virgin carbon fibre from lignin (5.9 €/kg, (Chen, 2014)). The recovered fibres from this technique are thus competitive with limestone or low grade of glass fibre. Yet some recent studies have highlighted the high retention of properties of carbon fibre that can be obtained by this recycling technique (Oliveux et al., 2015a) so that the reuse of recycled carbon fibres from SCW is promising.

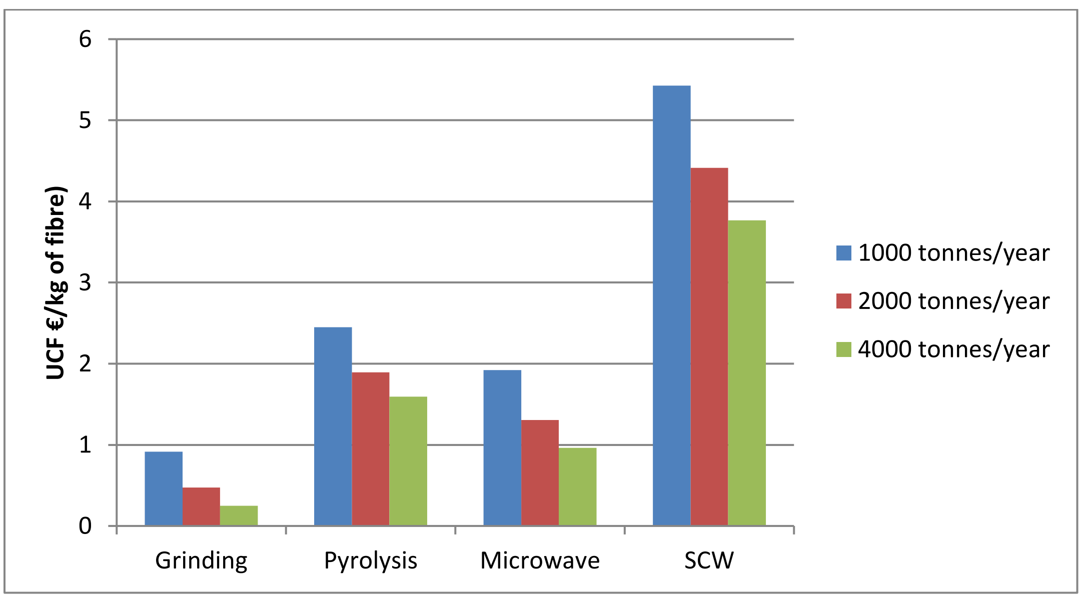


Figure 3-5: Sensitivity of Recovery Pathways on input capacity

3.3.3.2. Carbon fibre recovery rate

The impact of carbon fibre recovery rate in recycling techniques is now studied with UCF for economic assessment (Figure 3-6) and GWPTOT for environmental assessment (Figure 3-7). This parameter will be varied from 10 % to 100 % in a fixed capacity of 2000 tonnes/year for all the recovery pathways. In this scenario, the recovered fibre fraction which can be used as carbon fibre applications is characterized by a carbon fibre recovery rate (γ) of total recovered fibre quantity; the remaining part of recovered fibre (1-γ), which cannot be used as carbon fibre, is considered to substitute glass fibre. The UCF indicator is evaluated by considering the profit from by-products (filler, oligomers, low-valued fraction of recovered fibre (1-γ)).

For economic assessment, three ranges of carbon fibre price are determined by the minimum ideal cost that the industry aims to reach, i.e., 4.5 €/kg according to (Berreur et al., 2002) and the lowest price of virgin carbon fibre from lignin (the cheapest precursor for carbon fibre) (i.e., 5.9 €/kg, (Chen, 2014)): 0 – 4.5 €/kg, 4.5 – 5.9 €/kg and above 5.9 €/kg. These three ranges are separated by the dotted lines of 4.5 €/kg and 5.9 €/kg in Figure 3-6. The UCF values in the first range can be viewed as the most competitive prices to substitute virgin carbon fibre by RCF. The second one can be considered as a kind of "safe" price that recycled fibre can be accepted to replace conventional carbon fibre. The recycled carbon fibre with an UCF above the cost of lignin-based carbon fibre (5.9 €/kg) may have difficulties to win over this carbon fibre type from an economic viewpoint.

In this sensitivity study, the profits from by-products included in UCF evaluation cannot cover all the recycling costs due to their low value on regarding that the UCF values cannot reach à zero. However, they allow reducing slightly the UCF value in compared between the UCF estimated in the precedent part without by-products contribution and the corresponding UCF at 100% recovery rate in this part.

Logically, the increase in carbon fibre recovery rate reduces the UCF for recovered carbon fibre fraction. Whatever the value of carbon fibre recovery rate, the UCF exhibits the highest value for SCW, followed in decreasing order by pyrolysis, microwave and grinding. This can be explained by high operation cost and investment cost in SCW technique. For low carbon fibre recovery rates (10 % and 20 %) of SCW, the estimated costs of recycled carbon fibre is higher than the price of the virgin PAN carbon fibre (15.5-19.5 €/kg, (Chen, 2014)). This could suggest to adopt recycled carbon fibre from SCW in carbon fibre market if the carbon fibre recovery rate of this technique reaches around 60 % and preferably 80 % from which UCF is below 4.5 €/kg.

In the thermal recycling techniques, the recovery of oligomers allows reducing largely the UCF of microwave, which has moderate operation cost, compared to the UCF of pyrolysis, which does not recover any by-products and requires high energy for operation. Grinding is the most modest technique for which UCF values are always below 4.5 €/kg, from 2.1 €/kg to 0.43 €/kg at 10 % and 100 % carbon fibre recovery rate respectively. Even at very low yield of recycled carbon fibre, this technique can still offer low price for utilisation of recycled fibre in carbon fibre applications. For the most expensive techniques, i.e. SCW and pyrolysis, a high carbon fibre recovery rate is important to get competitive prices of recycled carbon fibre.

In the assessment of GWP impacts, the GWPTOT values of all recycling techniques are negative due to the high value of avoided impacts from replacement of virgin materials by recovered products. Furthermore, the high gap in GWP impacts between carbon fibre production (31 kg CO_2 eq./kg, (Das, 2011)) and glass fibre production (2.6 kg CO_2/kg (Kellenberger et al., 2007)) promotes the increase of yield for recycled carbon fibre instead of using recovered fibre as substitution of glass fibre in order to gain important avoided GWP impacts.

Less GWP impact results from pyrolysis among the recovery pathways because of the high energy consumption, the combustion of matrix and the absence of by-products recovery. By contrast, grinding with low energy input has the most significantly reduced GWP impacts, especially at high carbon fibre recovery rates. Although grinding is the most environmental friendly process, the use of fibre fraction at high yield is difficult due to important degradation of fibre properties through this process. For microwave, the oligomers recovery makes this technique attractive with similar GWPTOT with the low-energetic technique, i.e. grinding, at low carbon fibre recovery rates (10 % and 20 %). However, the oligomers yield released from SCW is higher than from microwave, the avoided impacts of the supplement oligomers in SCW compensate for the gap in GWPP between microwave and SCW. From 90 % of carbon fibre recovery rate, GWPTOT of SCW is lightly lower than microwave.

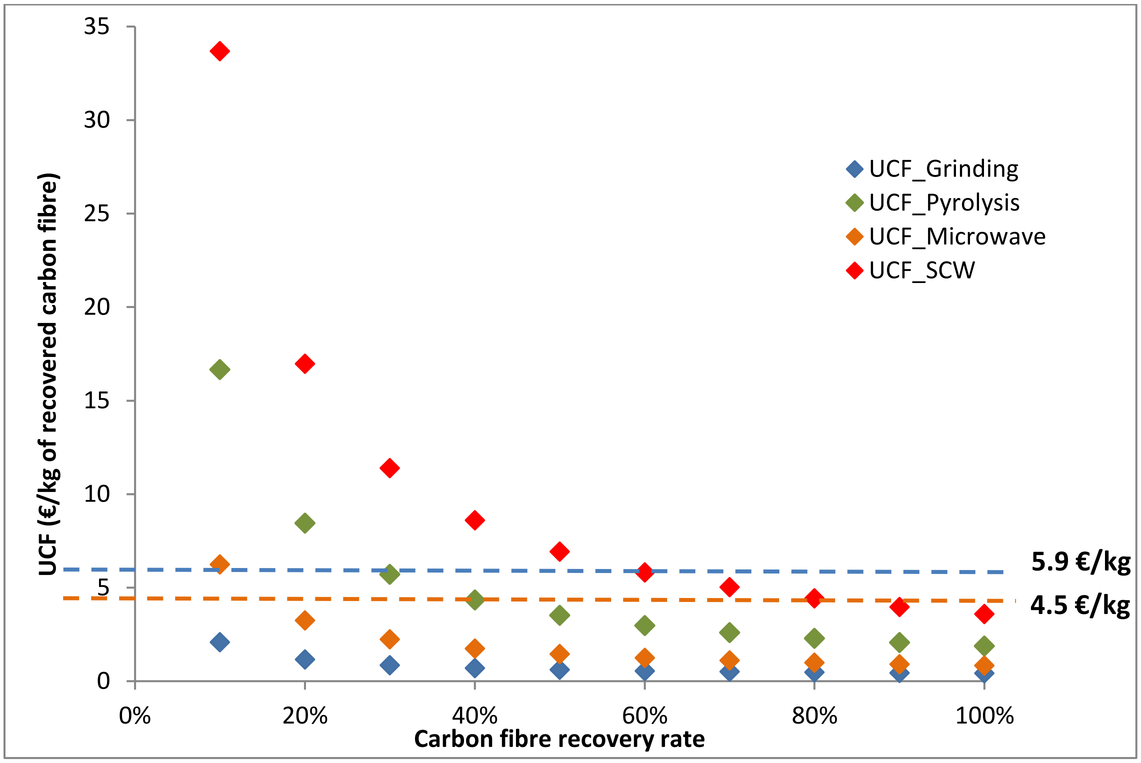


Figure 3-6: Sensitivity study of Economic Assessment by Carbon Fibre recovery rate

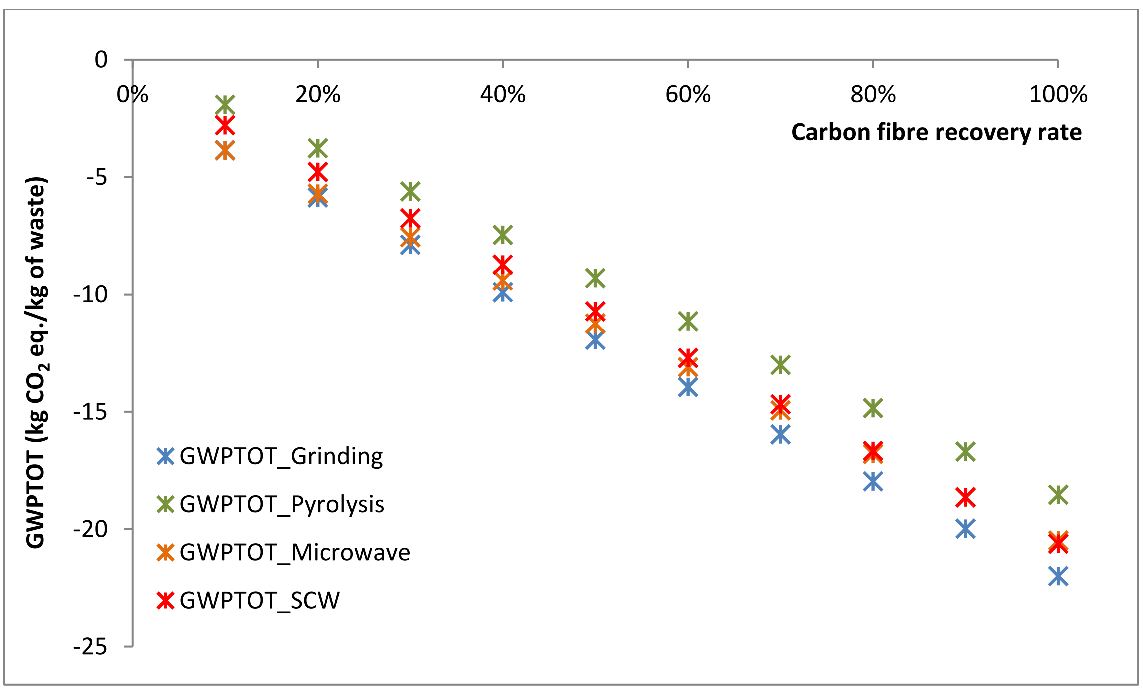


Figure 3-7: Sensitivity study of Environmental Assessment by Carbon Fibre recovery rate

3.4. Conclusion

While carbon fibres have been largely used in composite materials for about 40 years, the recycling of CFRP has only received attention more recently. The objective of this chapter was to study the potential benefits for CFRP waste management in economic and environmental viewpoints. Multiple pathways are assessed ranging from the options which cannot recover fibre in composites (i.e., landfill, incineration, co-incineration) to the recycling techniques (i.e., grinding, pyrolysis, microwave and supercritical water).

From both an economic and environmental viewpoint, different indicators represent different positions of stakeholders. Non recovery pathways such as landfill and incineration (around 0.1 €/kg) which are cheaper than recycling techniques may be priority for waste producers who aim to reduce waste deposit. These pathways however cannot give benefit for recyclers who need fibre recovery techniques. The auxiliaries input of recycling techniques must be small enough while the recovery rate is high in order to have competitive price for recycled fibre and reduce GWP impacts of process via the avoided impacts.

The cost and GWP assessments of the modelled pathways show two main trends:

1. The Non recovery techniques apart from co-incineration, i.e. landfill and incineration are the cheapest options but have high GWP impacts due to the loss or the low value of recovered products.

2. The techniques with high yield of recovery require more capital, especially supercritical water, than other pathways, but allow important reduction of GWP impacts on considering the avoided impacts.

These results highlight the potential conflicts between economic and environmental indicators as there is no technique having both low cost and GWP impacts.

The economic assessments show highly potential for substitution of virgin carbon fibre or virgin glass fibre by recycled carbon fibres. The prices of recovered fibres from the modelled recycling techniques are found to be competitive compared with the prices of virgin fibres. However, the reutilisation of RCF in different markets of glass fibres and carbon fibres depend on recycling technologies, plant scale, and recovery rate. Due to the simple process, RCF from grinding can be sold with a price of lower than 1 €/kg at low capacity (1000 tonnes/year). Even with low substitution rate of carbon fibre (10%) at moderate capacity (2000 tonnes/year), grinding can give the competitive price (2.1 €/kg) for carbon fibre market. However, in the advanced recycling technologies, high recycling capacity and high carbon fibre recovery rate are required to overcome the price of virgin fibre and recycled fibre from cheaper techniques. Indeed, recycled fibres from SCW cannot be used in recycled glass fibre market due to the very high treatment cost (over 3.5 €/kg of fibre) even at high capacity of 4000 tonnes/year.

Considering the avoided impacts, GWP assessment clearly promotes recycling activities by recovery of carbon fibre and avoids utilisation of Non recovery routes. The more values of the substituted products have, the more reduction of GWP impacts can get. This assessment also shows the high interest of recycling over the conventional production of carbon fibre and glass fibre with negative GWP impacts. Under this indicator, the combustion is significant factor to evaluate the technologies. Otherwise, as waste treatment techniques are complex processes which produce not only GHG emissions but also noise pollution, human toxicity impacts, etc., a complete environmental assessment is needed to have a panorama of the various impacts.

Without consideration of quality for recovered fibre, the expensive recycling techniques, i.e. supercritical water, have fewer advantages than the low-cost techniques like grinding. Quality of recycled fibre may be strict criterion for its reutilisation in mechanical application. However, recycled fibres can be reconditioned after recycling process to adapt different applications. Therefore, this study does not consider quality of recycled fibres in order to take a possible large view from panorama of economic and environmental aspects on CFRP waste management without limit of applications for recycled fibres.

In reality, the CFRP waste streams are composed of not only the cured composite which is assumed in this study, but also the uncured production composite (prepreg) and the End-of-life waste which may contain metallic inserts or other contaminants. Each waste stream has specific treatment and may be more compatible with one recycling technique than the other. There is no ideal CFRP waste treatment solution: the choice of technique depends on the composition of waste generated and the context of market for recovered fibre. In order to study the impacts from the complexity of waste flows in CFRP waste treatment system, the modelling of the system with the use of an LP (Linear Programming)/MILP (Mixed Integer Linear Programming) formulation will be carried out. The objective is to design a CFRP waste management system which is a good compromise between economic and environmental issues with the variability of waste flows and the different waste treatment techniques.

CHAPTER 4

Optimal design of CFRP waste supply chain through a mono-period optimisation approach

Abstract

The increased use of Carbon Fibre Reinforced Polymers (CFRP) has raised the environmental concerns on waste disposal and consumption of non-renewable resources as well as economic awareness for the need to recycle CFRP wastes stemming from aircraft. This study develops an optimisation framework of CFRP waste management with the simultaneous objective of minimising cost and Global Warming Potential (GWP) impacts along the entire network. Diverse CFRP waste types are involved to be further treated by the current available techniques of fibre/energetic recovery techniques and disposal option. The scenarios that are investigated are based on the current situation in France. The large inventory of the existing sites concerning aerospace CFRP industry is carried out to predict the waste quantity that is likely to be generated. The objective is to develop waste allocation strategies, which are both good for economic and environmental aspects. The results obtained show that the economic interest and the environmental effect are conflicting, for which transportation turns out to be an important factor.

Résumé:

L’augmentation de l’utilisation de polymères renforcés de fibres de carbone (CFRP) soulève des préoccupations environnementales sur l'élimination des déchets et la consommation de ressources non renouvelables ce qui renforce la nécessité de recycler les déchets CFRP, notamment issus de la filière aéronautique. Cette étude propose un cadre d'optimisation de la gestion des déchets de CFRP avec l'objectif simultané de minimiser le coût et les impacts liés au potentiel de réchauffement global (GWP) du système. Divers types de déchets CFRP sont impliqués pour être traités par les techniques actuellement disponibles pour la valorisation des fibres ou de l’énergie et l’enfouissement. Les scénarii étudiés sont basés sur la situation actuelle en France. Un large inventaire des sites existants concernant l'industrie de CFRP aéronautique est réalisée afin de prévoir la quantité de déchets susceptibles d'être produits. Le but est d'élaborer des stratégies d'allocation des déchets, qui sont à la fois satisfaisantes tant du point de vue économique et qu’environnemental. Les résultats obtenus montrent que l'intérêt économique et l'effet environnemental sont contradictoires dans lequel le transport apparaît comme un facteur important.

Nomenclature

Indices/Sets

$c \in \mathscr{C}, \mathscr{C} = \left\{ \begin{matrix} \text{Market 1,Market 2,} \\ \text{Market 3,Market 4} \end{matrix} \right\}$	Market of Recovered Product
$e \in \mathscr{E}, \mathscr{E} = \{\text{Landfill, Incineration, Co-incineration}\}$	No-fibre Recovery Pathways
$f \in$ {carbon fibre production, prepreg production, CFRP component production}	Manufacturer type
$i \in \mathscr{I}, \mathscr{I} = \{\text{Cured and chopped composite}\}$	Intermediate product
j	Variant in each aircraft model
$l, l', l'' \in \mathscr{L}, \mathscr{L} = \left\{ \begin{matrix} \text{NPCP,NOR,BRE,} \\ \text{ACAL,IDF,PL,CVL,} \\ \text{BFC,ALPC,ARA,} \\ \text{LRMP,PACA} \end{matrix} \right\}$	Location/region
m	Aircraft model
$p \in \mathscr{P}, \mathscr{P} = \{\text{Powdered,Fibrous,Fibre,Oligomers}\}$	Recovered Product from Fibre Recycling Technique
$r \in \mathscr{R}, \mathscr{R} = \{\text{grinding,pyrolysis,SCW}\}$	Fibre recycling technique
$s \in$ { small, medium, large}	Plant scale
t	Year of the study
$w \in \mathscr{W}, \mathscr{W} = \left\{ \begin{matrix} \text{dry fibre, uncured production,} \\ \text{cured production, EOL} \end{matrix} \right\}$	Waste type

Parameters

a_m	Number of variants in aircraft model ***m*** (variants)
$CAPD_l$	Maximum dismantling capacity at region ***l*** in one year (airplanes)
$CAPEL_{el}$	Capacity of no-fibre recovery technique ***e*** at region ***l***, (tonnes/year)
$CAPP_{fs}$	Annual capacity of one plant of type ***f*** at scale ***s*** in one year (tonnes/plant)
$CAPRL_{rl}$	Recycling capacity of fibre recovery technique ***r*** at region ***l***, (tonnes/year)
CQL_{cp}	Minimum quality of product ***p*** accepted by sector ***c*** (%)
$DISM_l$	Dismantling productivity, ($\in [0;1]$)
$DIST_{ll'}$	Distance between region ***l*** and region ***l'*** (km)
ECOM	Energy for compression (kwh/tonne)
EPR_w	Energy used for pre-treatment of waste ***w*** (kwh/tonne)
GWPE	GWP impacts of electricity (tonnes CO_2 eq./MJ)

$GWPIR_{ri}$	GWP impacts of treatment of intermediate product ***i*** by recycling technique ***r*** (tonnes CO_2 eq./tonne)
$GWPNRAU_{we}$	Avoided GWP impact of no-fibre recovery pathway ***e*** from waste ***w*** (tonnes CO_2 eq./tonne of waste)
$GWPNRU_e$	GWP impacts of treatment by no-fibre recovery pathway ***e*** (tonnes CO_2 eq./tonne of waste)
$GWPP_p$	GWP impacts of conventional production of product ***p*** (tonnes CO_2 eq./ton)
GWPTRU	GWP impacts of transport (tonnes CO_2 eq./tkm)
$GWPWR_{rw}$	GWP impacts of treatment of waste ***w*** by fibre recycling technique ***r*** (tonnes CO_2 eq./ton of waste)
M_{mj}	Operating empty weight of variant ***j*** in aircraft model ***m*** (tonnes/aircraft)
NOM_{fs}^{l}	Number of plants of type ***f*** at scale ***s*** in region ***l*** (plants)
n_t^m	Number of aircraft model ***m*** delivered in year ***t*** (aircraft)
pc_m	Proportion of CFRP weight in airframe in model ***m***, $(\in[0;1])$
PCOM	Cost of compression (€/tonne)
PE	Unit cost of electricity (€/kwh)
PIR_{ri}	Cost of treatment of recycling technique ***r*** for intermediate product ***i*** (€/tonne)
PNR_{ew}	Cost of no-fibre recovery technique ***e*** for waste ***w*** (€/ton)
PP_p	Price of recovered product ***p*** (€/tonne)
$PROD_{fs}$	Productivity of plant type ***f*** at scale ***s*** $(\in[0;1])$
ps_m	Proportion of airframe weight in operating empty weight in model ***m*** $(\in[0;1])$
PTR0	Cost of normal transport for recovered product (same for all type product p) (€/tkm)
PTR_w	Cost of transport for waste ***w*** (€/tkm)
PWM_{wf}	Generation rate of waste ***w*** from fabrication plant of type ***f*** (%)
PWR_{rw}	Cost of treatment of recycling technique ***r*** for waste ***w*** (€/tonne)
$QLPRP_{wp}$	Quality of recovered product ***p*** from waste ***w*** by pretreatment (%)
$QLRPI_{irp}$	Quality of recovered product ***p*** from intermediate ***i*** by recycling technique ***r*** (%)
$QLRPW_{wrp}$	Quality of recovered product ***p*** from waste ***w*** by recycling technique ***r*** (%)
QW_{wl}	Waste quantity ***w*** at region ***l*** (tonnes/year)
$RECM_l$	Rate of CFRP waste separation from aircraft, $(\in[0;1])$
$RIRP_{rpi}$	Conversion ratio from intermediate product ***i*** to final product ***p*** by fibre recycling technique ***r*** (%)
RNR_e	Revenue from no-fibre recovery pathway ***e*** (€/tonne)
$RWRP_{rpw}$	Conversion ratio from waste ***w*** to final product ***p*** by fibre recycling technique ***r***

	(%)
um_t	Average CFRP weight per retired aircraft in year ***t*** (tonnes)
XDP_{cpl}	Index of existence of sector ***c*** for product ***p*** at region ***l***
XIR_{ir}	Acceptance index of fibre recycling technique ***r*** for intermediate product ***i***, 1 if the technique ***r*** can treat the intermediate product ***i***, 0 otherwise
$XPRP_{wp}$	Index of conversion ***w*** to product ***p*** after pretreatment
XPR_w	Index for waste ***w*** which does not need recycling process after pretreatment step for recovery, 1 if the waste ***w*** does not go to the recycling process for recovery, 0 otherwise
$XTR_{ll'}$	Factor of transport, 1 if two regions (***l*** and ***l'***) are different; 0 otherwise
XWI_{wi}	Index of conversion waste ***w*** to intermediate product ***i*** after pretreatment
$XWNR_{we}$	Acceptance index of no-fibre recovery technique ***e*** for waste ***w***, 1 if the technique ***e*** can treat the waste ***w***, 0 otherwise
$XWPR_w$	Index for waste ***w*** which can go to pre-treatment step separately from recycling process, 1 if the separated pretreatment step is opened for the waste ***w***, 0 otherwise
XWR_{wr}	Acceptance index of fibre recycling technique ***r*** for waste ***w***, 1 if the technique ***r*** can treat the waste ***w***, 0 otherwise
Continuous variables	
$FIR_{irll'}$	Flow of intermediate product ***i*** transported from ***l*** to recycling site ***r*** at ***l'***, (tonnes)
$FPDR_{wrpcll'}$	Flow of product ***p*** recovered from waste ***w*** by direct recycling technique ***r*** at location ***l*** and then distributed to market ***c*** at ***l'***, (tonnes)
$FPIR_{irpcll'}$	Flow of product ***p*** recovered from ***i*** by recycling technique ***r*** at location ***l*** and then distributed to market ***c*** at ***l'***, (tonnes)
$FPPR_{wpcll'}$	Flow of product ***p*** obtained from pretreated waste ***w*** at ***l*** directly transported to market ***c*** at ***l'***, (tonnes)
$FWDR_{wrll'}$	Flow of waste ***w*** from waste source ***l*** transported directly to recycling site ***r*** at ***l'***, (tonnes)
$FWNR_{well'}$	Flow of waste ***w*** to no-fibre recovery technique ***e*** at region ***l***, (tonnes)
$FWPR_{wll'}$	Flow of waste ***w*** transported from waste source at ***l*** to pretreatment site at ***l'***, (tonnes)

4.1. Introduction

This CFRP context that has been previously explained in the previous chapter motivates the essential of modelling for CFRP waste management in aerospace sector in order to reduce the increasing flow of waste and to regain economic and environmental benefits from recycling. However, this model is complex with multiple possible routes for CFRP waste treatment. Each waste type has different characteristics and needs its own operation conditions. The market of recovered fibre is not still mature as the utilisation of recycled carbon fibres in industry generates some challenges which come from their lower quality than that of virgin carbon fibres (McConnell, 2010) and their variability affecting many factors such as length, length distribution, surface quality (adhesion of fibre and matrix), as well as their origin (different grades of fibres are found at composite scraps from different manufacturers) (Oliveux et al., 2015a). In aerospace, the closed loop of carbon fibre material is limited because of high requirements in structural components and the degradation of fibre through recycling process. Recycled carbon fibre can be used in the applications in aerospace or other sectors which do not demand high quality in mechanical properties such as interior, automotive, construction… which can give more environmental benefits than the disposal solutions, e.g. landfill, incineration.

Considering these challenges, this study aims to develop an optimisation approach of CFRP waste management in aerospace with two objectives, i.e. minimising both cost and GWP impacts, in order to assess both economic and environmental factors in the entire network. A linear programming model has been developed to determine the optimal material flow of CFRP waste going into different routes under each strategy. This framework is applied in France where the aviation industry is strong with Airbus and important suppliers in global aviation.

This paper is organised as follows. Its content has been published in this following publication (Vo Dong et al., 2016)[1]. Section 4.2 presents the general concept of the network and its mathematical model with the associated constraints and objective function. The data and assumptions used in the case of France can be found in detail in Section 4.3. Section 4.4 presents the results of the network design under different strategies, following first a mono-objective optimisation strategy with economic cost and GWP impacts as separate criteria; second the criteria are associated in a bi-criteria optimisation formulation. This assessment is extended by a sensitivity study relative to the influence of recycling capacity. Finally, conclusions and perspectives are highlighted in Section 4.5 focusing on the extension of the model.

[1] Phuong Anh VO DONG, Catherine AZZARO-PANTEL, Marianne BOIX, Leslie JACQUEMIN, Anne-Laure CADÈNE, A Bicriteria Optimisation Approach for Waste Management of Carbon Fibre Reinforced Polymers Used in Aerospace Applications: Application to the Case Study of France, Waste and Biomass Valorization, 1-22, 2016.

4.2. Problem formulation

4.2.1. System definition and assumptions

The waste management model is developed through three main layers: waste types, waste treatment techniques and recovered products. The economic and environmental assessments are evaluated by all the activities concerning these three layers: transportation of waste from source to plant for treatment, waste treatment process and recovered products output from waste treatment (Figure 4-1).

The model is formulated here as a static problem in which there is no variation of waste quantity and waste treatment capacity during the considered horizon time. All the wastes produced at the various sources have to follow the treatment system completely and cannot be stored at source. The waste treatment techniques are assumed to be available with a fixed capacity and the problem of deployment is not considered in this study.

According to (Potter and Ward, 2010), waste in the aerospace composites industry can be defined generally as either end-of-life or manufacturing waste. The latter is constituted of different scrap types including woven prepreg, unidirectional prepreg, composite manufacturing part, clean fibre and fabric selvedge (McConnell, 2010). In this study, the composition of the input waste flow only considers the status of polymeric matrix via its curing level in scrap since the thermosetting polymer is principal resin used in aerospace application. The form of carbon fibre, e.g. fabric, or unidirectional form is not applied to classify the waste type. Based on carbon fibre chain in aerospace industry, the model considers four waste types: dry fibre waste, uncured production waste, cured production waste and cured end-of-life waste.

As carbon fibre is the most value component in CFRP, we focus on how the recycling rate of carbon fibre varies in the system under different scenarios. There are two main routes for waste treatment, i.e., No-Fibre Recovery and Fibre Recovery. The techniques considered in the first group are landfill, incineration and co-incineration. Heat or heat/material couple valorisation can be obtained through incineration or co-incineration respectively. Otherwise, Fibre Recovery pathways allow the recovery of carbon fibre through pre-treatment steps and recycling process. Due to the nature of waste types and technical constraints of recycling process, each waste type has to go into firstly pre-treatment step and then recycling process. Pre-treatment activities encompass shredding and curing. The techniques of recycling process considered are grinding, pyrolysis and recycling using supercritical water. Beside recovery of carbon fibre, by-products can be obtained. The modelling of these techniques is based on literature. Data collection is mainly obtained from a literature analysis based on an experimental approach for CFRP recycling.

Due to its nature, each waste type has its own constraints for the selection of the possible routes (Figure 4-1). All waste types are required to go through shredding before going to recycling process. However, dry fibre waste can be recovered only by this step and does not need to go into any further process. The curing activity is applied on uncured waste due to the hazardous classification of this waste for transportation and to the requirements of some processes which cannot operate the uncured waste. Pre-treatment activities are assumed to be available at all recycling plants. All waste types are free to choose either direct recycling way, which means the pre-treatment step and recycling process at the same location or the indirect recycling way by which waste is pre-treated at one location and then transported to other locations for recycling. Considering the presence of flame retardant, end-of-life waste cannot go to the thermal process, i.e. incineration, co-incineration and pyrolysis.

The quality of recovered fibre is also considered in the model and may vary according to the selected process. The retention of tensile strength in comparison with virgin fibre is used to quantify the quality of recycled fibre. This parameter can help to distinguish pyrolysis from supercritical water to separate the recovered fibres from. Although a fibrous fraction can be obtained by grinding, its quality is assumed to be too low for high-value carbon fibre market and can be used in lower value market considering the degradation of fibre and the impurity of matrix in this fraction.

For transportation, the geographic unit of the model is based on a regional grid. The distance between the regions corresponds to the average distance between their two prefectures. The model does not consider the intra-mobility in each region. Although each waste type is generated by specific plants, e.g. end-of-life waste from aircraft dismantling site, uncured waste from prepreg/composite production plants, etc., the collection of all waste type in each region is not considered in the model and all of waste in each region is assumed to be available at the same location, i.e. its prefecture. In the same way, the transportation of waste from source to treatment plant and the distribution of the recovered product to market at the same region are not considered in the model.

There is no storage of waste at source and all the waste generated at each region has to be treated completely through either no-fibre recycling or fibre recycling pathways until there is no waste left in the static model. Two quantitative constraints are formulated at upstream: conservation of waste quantity allocated according to different techniques and to the capacity of waste treatment plants. As the aerospace industry has not been clearly regulated for the waste problem yet, there is no constraint on the recycling rate in the model. This variable factor is kept track of in order to study carbon fibre recyclability in the system in function of different criteria.

The economic criterion taken into account includes all the costs of the entire system, i.e., transportation, waste treatment, products distribution activities. The environmental impact is based on GWP impacts and is evaluated through both impacts from the activities of the whole system and the avoided impacts gained by the replacement of conventional products by the recovered products, which are assumed to have the same nature. An equivalent amount of the recovered product replaces the virgin product.

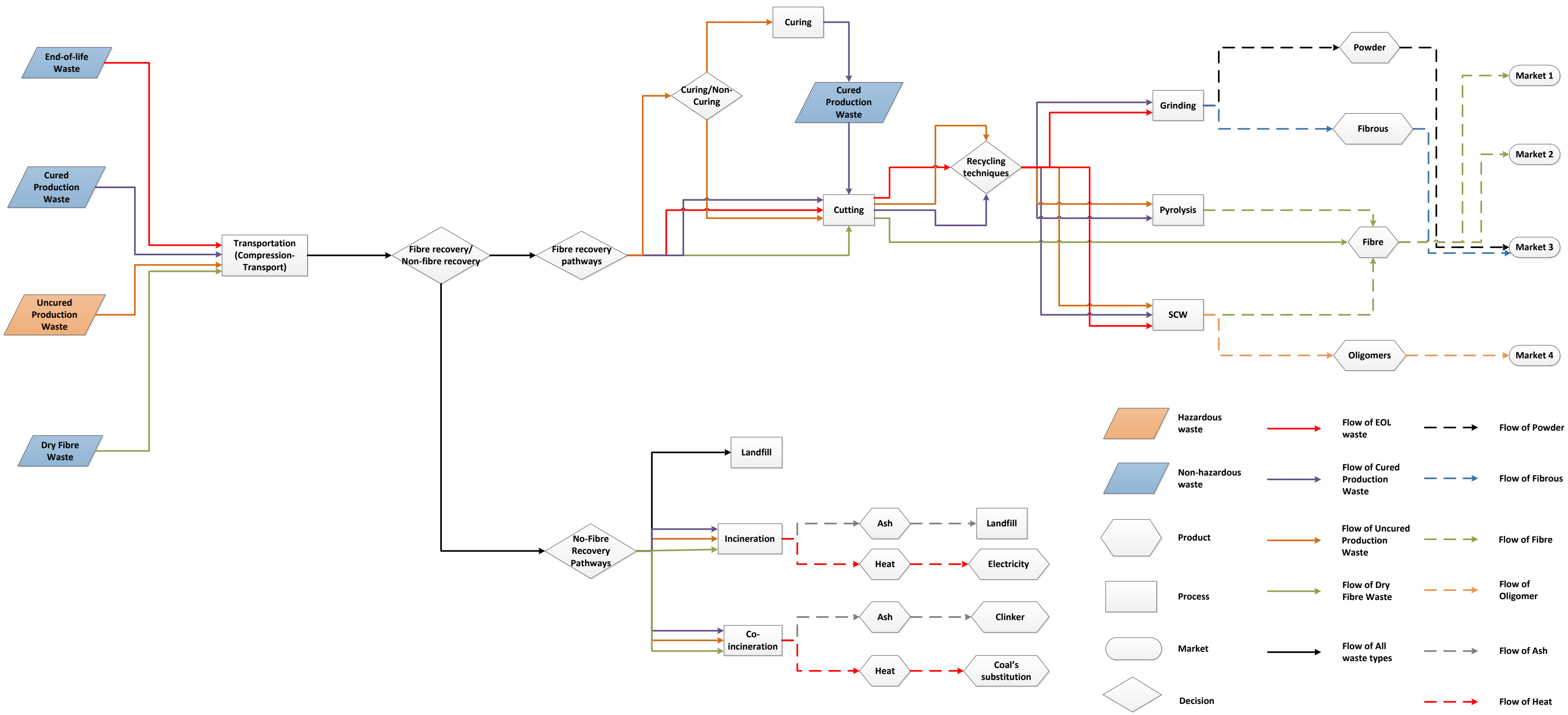


Figure 4-1: System of CFRP waste management

4.2.2. Mathematical model

The CFRP waste management system in this study is formulated as a single-period linear problem which predicts the distribution of wastes in multiple pathways of waste treatment techniques under two objectives: minimisation of the cost and minimisation of the GWP impacts. Four types of constraints are included in this model, i.e. mass conversation, treatment capacities, non-negative flows, and acceptability characteristics of techniques.

4.2.2.1. Constraints

a. Waste quantity conservation

All the wastes generated at source l cannot be stored at source and have to be treated completely through either No-Fibre recovery or Fibre Recovery pathways. There are two options for the secondary routes: pretreatment step and recycling process are separated for flow $\boldsymbol{FWPR_{wll'}}$; direct recycling in which pretreatement can be integrated in function of the adaptability of process r with waste w. Therefore, each output flow of each waste type w at source l has to be equal to the waste quantity of that waste type at the same location (4.1).

$$\sum_{r\in\mathcal{R}}\sum_{l'\in\mathcal{L}} FWDR_{wrll'} + \sum_{l'\in\mathcal{L}} FWPR_{wll'} + \sum_{e\in\mathcal{E}}\sum_{l'\in\mathcal{L}} FWNR_{well'} = QW_{wl}, \forall w\in\mathcal{W}, \forall l\in\mathcal{L} \quad (4.1)$$

b. Capacity constraints

The waste treatment capacity at each plant is applied for all waste inputs. The total waste streams which go into No-Fibre recovery techniques are under constraints (4.2). The flow of waste that pre-treated separately is lower than the capacity of pre-treatment which is equal to the total of capacity of all recycling techniques at the same location (4.3). All stream inputs of each recycling plant are inferior to its capacity (4.4).

$$\sum_{w\in\mathcal{W}}\sum_{l\in\mathcal{L}} FWNR_{well'} \le CAPEL_{el'}, \forall e\in\mathcal{E}, \forall l'\in\mathcal{L} \quad (4.2)$$

$$\sum_{w\in\mathcal{W}}\sum_{l\in\mathcal{L}} FWPR_{wll'} \le \sum_{r\in\mathcal{R}} CAPRL_{rl'}, \forall l'\in\mathcal{L} \quad (4.3)$$

$$\sum_{i\in\mathcal{I}}\sum_{l\in\mathcal{L}} FIR_{irll'} + \sum_{w\in\mathcal{W}}\sum_{l\in\mathcal{L}} FWDR_{wrll'} \le CAPRL_{rl'}, \forall r\in\mathcal{R}, \forall l'\in\mathcal{L} \quad (4.4)$$

c. Non negativity constraints

All streams of waste, intermediate product and recovered final product cannot take negative values according to constraints (4.5)-(4.11).

$$FWNR_{well'} \geq 0, \forall w \in \mathscr{W}, \forall e \in \mathscr{E}, \forall l, l' \in \mathscr{L} \quad (4.5)$$
$$FWPR_{wll'} \geq 0, \forall w \in \mathscr{W}, \forall l, l' \in \mathscr{L} \quad (4.6)$$
$$FWDR_{wrll'} \geq 0, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall l, l' \in \mathscr{L} \quad (4.7)$$
$$FIR_{irll'} \geq 0, \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall l, l' \in \mathscr{L} \quad (4.8)$$
$$FPPR_{wpcll'} \geq 0, \forall w \in \mathscr{W}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall l, l' \in \mathscr{L} \quad (4.9)$$
$$FPDR_{wrpcll'} \geq 0, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall l, l' \in \mathscr{L} \quad (4.10)$$
$$FPIR_{irpcll'} \geq 0, \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall l, l' \in \mathscr{L} \quad (4.11)$$

d. Acceptability constraints

According to their type, the wastes can be accepted or not in a waste treatment pathway due to the difficulty of treatment. The waste streams to each route are restricted by the constraints (4.12)-(4.14). The adaptability of intermediate products after pretreatment step in recycling technique is under constraint (4.15).

The constraints (4.16)-(4.18) show the acceptability of recovered product streams in the corresponding market. Besides the types of recovered products, each market requires a minimum quality of products so that they can be accepted to that market. These constraints are shown by (4.19)-(4.21).

$$\sum_{l' \in \mathscr{L}} FWNR_{well'} \leq XWNR_{we} \times QW_{wl}, \forall w \in \mathscr{W}, \forall e \in \mathscr{E}, \forall l \in \mathscr{L} \quad (4.12)$$
$$\sum_{l' \in \mathscr{L}} FWDR_{wrll'} \leq QW_{wl} \times XWR_{wr}, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall l \in \mathscr{L} \quad (4.13)$$
$$FWPR_{wrll'} \leq XWPR_{w} \times QW_{wl}, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall l, l' \in \mathscr{L} \quad (4.14)$$
$$\sum_{l' \in \mathscr{L}} FIR_{irll'} \leq QWIR_{il} \times XIR_{ir}, \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall l \in \mathscr{L}$$
with
$$QWIR_{il} = \sum_{w \in \mathscr{W}} \left[\sum_{l' \in \mathscr{L}} FWPR_{wl'l} \times (1 - XPR_{w}) \right] \times XWI_{wi}, \forall i \in \mathscr{I}, \forall l \in \mathscr{L} \quad (4.15)$$
$$\sum_{w \in \mathscr{W}} \sum_{l \in \mathscr{L}} FPPR_{wpcll'} \leq XDP_{cpl'} \times M, \forall c \in \mathscr{C}, \forall p \in \mathscr{P}, \forall l' \in \mathscr{L}$$
with
$$\sum_{c \in \mathscr{C}} \sum_{l' \in \mathscr{L}} FPPR_{wpcll'} = \left(\sum_{l'' \in \mathscr{L}} FWPR_{wl''l} \times XPR_{w} \right) \times XPRP_{wp}, \forall w \in \mathscr{W}, \forall p \in \mathscr{P}, \forall l \in \mathscr{L} \quad (4.16)$$
$$\sum_{w \in \mathscr{W}} \sum_{r \in \mathscr{R}} \sum_{l \in \mathscr{L}} FPDR_{wrpcll'} \leq XDP_{cpl'} \times M, \forall c \in \mathscr{C}, \forall p \in \mathscr{P}, \forall l' \in \mathscr{L}$$
with
$$\sum_{c \in \mathscr{C}} \sum_{l' \in \mathscr{L}} FPDR_{wrpcll'} = \sum_{l'' \in \mathscr{L}} FWDR_{wrl''l} \times RWRP_{rpw} / 100, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall l \in \mathscr{L} \quad (4.17)$$
$$\sum_{i \in \mathscr{I}} \sum_{r \in \mathscr{R}} \sum_{l \in \mathscr{L}} FPIR_{irpcll'} \leq XDP_{cpl'} \times M, \forall c \in \mathscr{C}, \forall p \in \mathscr{P}, \forall l' \in \mathscr{L}$$
with
$$\sum_{c \in \mathscr{C}} \sum_{l' \in \mathscr{L}} FPIR_{irpcll'} = \sum_{l'' \in \mathscr{L}} FIR_{wrl''l} \times RIRP_{rpi} / 100, \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall l \in \mathscr{L} \quad (4.18)$$

$$FPDR_{wrpcll'} \times QLRPW_{wrp} \geq FPDR_{wrpcll'} \times CQL_{cp} / 100 \quad \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall l,l' \in \mathscr{L} \tag{4.19}$$

$$FPIR_{irpcll'} \times QLRPI_{irp} / 100 \geq FPIR_{irpcll'} \times CQL_{cp} / 100 \quad \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall l,l' \in \mathscr{L} \tag{4.20}$$

$$FPPR_{wpcll'} \times QLRPP_{wp} \geq FPPR_{wpcll'} \times CQL_{cp} / 100, \quad \forall w \in \mathscr{W}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall l,l' \in \mathscr{L} \tag{4.21}$$

M is a big number that is used to impose the qualitative constraints in the mathematical model. In this case, it is applied to the restrictions of markets for recovered products.

4.2.2.2. Objective functions

The bi-criteria optimisation approach in the model is carried out through all activities in the system boundary (Figure 4-1) from transportation, waste treatment process to distribution of recovered product with two indicators, i.e. the economic cost and the GWP impacts. The objective functions are minimisation of the cost and minimisation of the GWP impacts. These objectives functions consist of variable costs ((4.22) – (4.27)) and variable GWP impacts ((4.28) – (4.34)) that depend on flows of wastes and products in the network. The input data is collected from literature in general and evaluated from Simapro v7.3 with ReCiPe Midpoint (H) v.1.06 assessment method for unit GWP impacts.

a. Cost minimisation

COST =

$$\sum_{w\in\mathscr{W}} \sum_{i\in\mathscr{I}} \sum_{r\in\mathscr{R}} \sum_{e\in\mathscr{E}} \sum_{l,l'\in\mathscr{L}} \left\{ \begin{bmatrix} \left(FWNR_{well'} + FWPR_{wll'} + FWDR_{wrll'}\right) \times PTR_w + \\ +\left(FIR_{irll'} \times PTR0\right) \end{bmatrix} \times DIST_{ll'} \right\} + \tag{4.22}$$

(Transport cost)

$$+\left[\sum_{w\in\mathscr{W}} \sum_{e\in\mathscr{E}} \sum_{l,l'\in\mathscr{L}} \left(FWNR_{well'} \times PNR_{ew}\right)\right] + \tag{4.23}$$

(Cost of No-Fibre recovery pathways)

$$+\left\{\sum_{w\in\mathscr{W}} \sum_{i\in\mathscr{I}} \sum_{e\in\mathscr{E}} \sum_{r\in\mathscr{R}} \sum_{l,l'\in\mathscr{L}} \left[\begin{pmatrix} FWNR_{well'} + FWPR_{wll'} + \\ +FWDR_{wrll'} + FIR_{irll'} \end{pmatrix} \times XTR_{ll'} \times PCOM \right]\right\} + \tag{4.24}$$

(Compression cost)

$$+\left[\sum_{w\in\mathscr{W}} \sum_{l,l'\in\mathscr{L}} \left(FWPR_{wll'} \times EPR_w \times PE\right)\right] + \tag{4.25}$$

(Pretreatment cost)

$$+\left\{\sum_{r\in\mathscr{R}} \sum_{l,l'\in\mathscr{L}} \left[\sum_{w\in\mathscr{W}} \left(FWDR_{wrll'} \times PWR_{rw}\right) + \sum_{i\in\mathscr{I}} \left(FIR_{irll'} \times PIR_{ri}\right)\right]\right\} + \tag{4.26}$$

(Cost of recycling process)

$$+\left\{\sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{r\in\mathscr{R}}\sum_{p\in\mathscr{P}}\sum_{c\in\mathscr{C}}\sum_{l,l'\in\mathscr{L}}\left[\begin{pmatrix}FPPR_{wpcll'}+FPDR_{wrpcll'}+\\+FPIR_{irpcll'}\end{pmatrix}\times DIST_{ll'}\times PTR0\right]\right\} \tag{4.27}$$

(Cost of distribution of recovered product)

b. Minimisation of the GWP impacts

The GWP is expressed as follows:

GWP =

$$\left[\sum_{w\in\mathscr{W}}\sum_{e\in\mathscr{E}}\sum_{l,l'\in\mathscr{L}}\left(FWNR_{well'}\times GWPNRU_{e}\right)\right]+ \tag{4.28}$$

(No-fibre recovery activities impacts)

$$+\left\{\sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{e\in\mathscr{E}}\sum_{r\in\mathscr{R}}\sum_{l,l'\in\mathscr{L}}\left[\begin{pmatrix}FWNR_{well'}+FWPR_{wll'}+\\+FWDR_{wrll'}+FIR_{irll'}\end{pmatrix}\times\left(DIST_{ll'}\times GWPTRU\right)\right]\right\}+ \tag{4.29}$$

(Transport impacts)

$$+\left\{\sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{e\in\mathscr{E}}\sum_{r\in\mathscr{R}}\sum_{l,l'\in\mathscr{L}}\left[\begin{pmatrix}FWNR_{well'}+FWPR_{wll'}+\\+FWDR_{wrll'}+FIR_{irll'}\end{pmatrix}\times XTR_{ll'}\times ECOM\times 3.6\times GWPE\right]\right\}+ \tag{4.30}$$

(Compression impacts)

$$+\left[\sum_{w\in\mathscr{W}}\sum_{l,l'\in\mathscr{L}}\left(FWPR_{wll'}\times EPR_{w}\times 3.6\times GWPE\right)\right]+ \tag{4.31}$$

(Pretreatment activity impacts)

$$+\left\{\sum_{r\in\mathscr{R}}\sum_{l,l'\in\mathscr{L}}\left[\sum_{w\in\mathscr{W}}\left(FWDR_{wrll'}\times GWPWR_{rw}\right)+\sum_{i\in\mathscr{I}}\left(FIR_{irll'}\times GWPIR_{ri}\right)\right]\right\}+ \tag{4.32}$$

(Recycling activity impacts)

$$+\left\{\sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{r\in\mathscr{R}}\sum_{p\in\mathscr{P}}\sum_{c\in\mathscr{C}}\sum_{l,l'\in\mathscr{L}}\left[\left(FPPR_{wpcll'}+FPDR_{wrpcll'}+FPIR_{irpcll'}\right)\times DIST_{ll'}\times GWPTRU\right]\right\} \tag{4.33}$$

(Distribution impacts)

$$-\left\{\sum_{w\in\mathscr{W}}\sum_{l,l'\in\mathscr{L}}\left[\begin{array}{l}\sum_{e\in\mathscr{E}}\left(FWNR_{well'}\times GWPNRAU_{we}\right)+\\+\sum_{r\in\mathscr{R}}\sum_{p\in\mathscr{P}}\sum_{c\in\mathscr{C}}\left[\left(FPPR_{wpcll'}+FPDR_{wrpcll'}+FPIR_{irpcll'}\right)\times GWPP_{p}\right]\end{array}\right]\right\} \tag{4.34}$$

(Avoided impacts from recovered products of No-Fibre recovery and Fibre recovery pathways)

4.2.3. Coupling multi-objective optimisation with MCDM strategy

The CFRP waste management is modelled as a linear problem with a deterministic approach fixing the waste quantity input of system. Two objective functions are considered in the model, i.e. minimising the cost and minimising the GWP impacts either separately or simultaneously. In this study, from a multiobjective point of view, the lexicographic method and the ε-constraint method have been combined to build the so-called the Pareto front which represents in the objective function space the non-dominated vectors of Pareto optimal solutions (so-called non-inferior, admissible or efficient solutions) which cannot be improved in one objective function without declining the performance in at least one of the remaining objectives (Van Veldhuizen, 1999).

Both lexicographic and ε-constraints are categorised as a priori preference method, in which multiobjective optimisation is transformed into a single objective optimisation problem by optimising one objective function after the other (lexicographic), or by optimising one objective by transforming all other objectives function into inequality constraints (ε-constraints). As two distinct lexicographic optimisations with distinct sequences of objective functions do not produce the same solution (Collette and Siarry, 2013), the solutions of lexicographic in this bi-criteria optimisation problem correspond to two extremities of Pareto front. Between the two extreme solutions, the other alternatives in Pareto front are obtained by ε-constraints method. The GWP impact function is minimised while the cost is limited under successive intervals till the lowest cost.

The multiobjective optimisation step is then followed by the use of a multiple criteria decision making (MCDM) procedure that consists in finding the best alternative among a set of feasible alternatives. Among the many approaches of MCDM, a variant of the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) method (Ren et al., 2007), called M-TOPSIS has been selected to rank the Pareto optimal solutions. TOPSIS is based upon the concept that the chosen alternative should have the shortest distance from the Positive Ideal Solution (PIS) (the lowest GWP impacts and the lowest cost in the studied case) and the furthest from the Negative Ideal Solution (NIS). The final ranking is obtained by means of the closeness index (Ren et al., 2007).

TOPSIS has been selected mainly for four the following reasons: TOPSIS logic is rational and understandable, the computation process is straightforward, the selection of the best alternatives for each criterion is carried out by a simple mathematical form, and the importance of weights is incorporated into the comparison procedures. In this study, the two criteria are considered to have the same importance weight; there is no preference one criterion over the other. M-TOPSIS is therefore the appropriate decision aid method to rank the alternatives in Pareto front and determine the compromise solution for the two objectives. It must be yet emphasized that MCDM techniques are not the panacea for all decision problems and the TOPSIS methods present certain drawbacks such as the phenomenon known as rank reversal.

4.3. Case study

The case study refers to the situation of France in 2016 for carbon fibre wastes from aerospace industry. The horizon time of this study is one year. The data input and the assumptions for the modelling of the case study, i.e. waste quantity, waste treatment pathways, transport, will be detailed in this section.

4.3.1. Waste Types

Apart from dry fibre scrap, the other waste types considered in the model are constituted of both carbon fibre and polymeric matrix. In the aerospace sector, CFRP are assumed to have 65 wt% of carbon fibre, and 35 wt% of thermoset matrix in average. The additives are considered to be negligible.

Carbon fibre in all waste types considered in this model is PAN-based, which due to high carbon yield, competitive process cost and superior physical properties, has been dominating the global market with 90%, the remaining 10% are made from rayon or pitch (Zoltek, 2016). This type of carbon fibre is therefore employed extensively in aerospace and industrial field and sporting / recreational goods (The Japan CF Manufacturers Association, 2014).

Through carbon fibre chain in aerospace (see Chapter 1), only wastes containing carbon fibre are considered in the boundary of system, i.e. dry fibre, uncured production CFRP, cured production CFRP and end-of-life CFRP, the other wastes such as PAN fibre and resin are excluded. Based on input-output relations of each step in carbon fibre chain, we determine the potential carbon fibre wastes of the system (see Chapter 1). Dry fibre comes from production of carbon fibre as production scrap, from production of prepreg and finished composite component as raw material scrap. Uncured production waste is generated during manufacturing prepreg as production scrap and finished composite component as raw material scrap. Cured production waste is produced from fabrication of finished CFRP component and end-of-life CFRP waste comes from retired aircraft after dismantling.

4.3.1.1. End-of-Life Waste from Aircraft Dismantling

End-of-life (EoL) CFRP waste is extracted from CFRP components of retired airplanes through their dismantling. In France, two sites are identified at Tarbes and Châteauroux, with a respective dismantling capacity estimated at 50 and 30 airplanes per year at full capacity. The rate of CFRP separation is assumed to reach 95 %. There is no consideration of reuse for CFRP waste, right after dismantling.

The rate of generation of CFRP waste per aircraft at a dismantling site is assumed to be equal to the average of all aircraft retired in 2006. Due to the variety in aircraft types and their CFRP content, the average weight of CFRP per aircraft at their retirement age (see expression (4.35)) is used to estimate the quantity of end-of-life waste according to expression (4.36).

Even if the retirement time of an aircraft depends on several factors such as the number of pressurisation and depressurisation cycles, greater efficiency, financial reasons, an average 25 -year life span of aircraft (t_r) is generally considered. The aircraft weight depends on its load, e.g. operating empty weight, maximum take-off weight… However, the weight of airframe structure is not well described by aircraft manufacturers. This parameter is therefore based on the operating empty weight with an index of proportion of airframe structure in this weight (psm). The operating empty weight, which includes structure, systems, engines, equipment, non-usable fuel, crew, is the nearest well-documented weight to the airframe structure weight. The index psm is assumed to be 0.9 for all aircraft types. Considering the light variation between the different variants in each aircraft model, the operating empty weight considered is the average of all the variants.

The CFRP content in structure of each aircraft model has been evaluated from literature review. This case study is applied for the commercial jets from McDonnell Douglas/Boeing and Airbus, which have CFRP content, the other aircraft from these manufacturers, which have no CFRP are not considered. Due to the lack of data, the assumptions are applied for the aircraft models, for which only the general information on composite proportion with yet no detail on CFRP content: the first models which adopt CFRP in secondary structure and the recent models which use CFRP in primary structure have respectively 50 wt% and 85 wt% of CFRP in the total composite content. Data concerning aircraft models, i.e. operating empty weight, proportion of CFRP, and the number of deliveries can be found in Appendices 1 and 2 respectively.

$$um_t = \frac{\sum_m \left[n^m_{t-t_r} \times \left(\frac{\sum_j M_{mj}}{a_m} \times ps_m \times pc_m \right) \right]}{\sum_m n^m_{t-t_r}} \tag{4.35}$$

$$QW^l_{w=EOL} = um_{t0} \times CAPD_l \times DISM_l \times RECM_l \tag{4.36}$$

4.3.1.2. Manufacturing Waste

The quantity of each type of production waste is calculated by the following formula (4.37):

$$QW^l_{w \in \mathscr{W} \setminus \{EOL\}} = \sum_f \sum_s CAPP_{fs} \times NOM^l_{fs} \times PROD_{fs} \times \frac{PWM^f_{w \in \mathscr{W} \setminus \{EOL\}}}{100} \tag{4.37}$$

To our knowledge, no data in concerning either waste quantity or waste production rate in the upstream steps of CFRP production, i.e. fibre and prepreg manufacturing is available. The wastes generated from these activities are assumed to represent 1 % of the products and 0.5 % of the raw materials of the output capacity of each plant. CFRP waste from manufacturing is assumed to be composed of 66 % prepreg, 18 % cured parts, 13 % trimmings, 2 % finished parts, and 1 % bonded honeycomb (Department of Defence, 2002). In this our model, these values are simplified and distributed to the three studied waste types: 66 % uncured, 27.5 % cured, and 6.5 % dry fibre on considering 50-50 distribution of cured CFRP and dry fibre in trimming waste and combining cured parts, finished parts, bonded honeycomb and trimmings (50%). In aerospace, the average manufacturing waste generated is estimated of 14 % of raw materials input of process (Potter and Ward, 2010). Based on this value, the proportion of all wastes generated from CFRP production is therefore calculated at 16.28 % of products output of process. The generation rates of each waste type in compared to product output are summarised in Table 4-1.

Table 4-1: Generation rate of waste of production plant PWMwf (%)

PWM_{wf} (%)	Dry Carbon Fibre Waste	Prepreg (Uncured Production CFRP Waste)	Cured Production CFRP Waste
Carbon Fibre Production (Fibre/Fabric)	1	0	0
Prepreg Production	0.5	1	0
CFRP Production	1.06	10.74	4.48

Only the big manufacturers of carbon fibre report the capacity of their plants. Similar data for fibre conditioning (fabric production), prepreg production, and finished aerospace CFRP component plants is not available. For this purpose, the plants in aerospace CFRP production chain (carbon fibre, prepreg, finished CFRP production) have been categorised into three classes of scale in function of supplier status for jets manufacturers i.e., prototype suppliers, outsourcing raw materials suppliers, subsidiaries. The assumed capacity of each class is proposed in Table 4-2. The number of plant types in each region in this study is presented in detail in Appendix 3. As carbon fibre manufacturing involves expensive processes, the manufacturing cost exclusively depends on a stable demand of markets. The current global carbon fibre production is evaluated at 68 % of its maximum capacity in 2016 according to the report of the project (+Composite, 2014). This yield has been applied for all steps in CFRP production chain in this study.

Table 4-2: Annual capacity of production plants CAPPfs (tonnes/plant)

$CAPP_{fs}$ (tonnes/plant)	Plant scale (s)		
	Small	Medium	Large
Carbon Fibre Production	1500	5000	9000
Prepreg Production	500	1000	1500
CFRP Components Production/Aircraft Manufacturer	50	250	500

4.3.1.3. Snapshot of waste sources in France

Following the aforementioned methods, the quantity waste estimated in each region of France can be visualised in Figure 4-2.

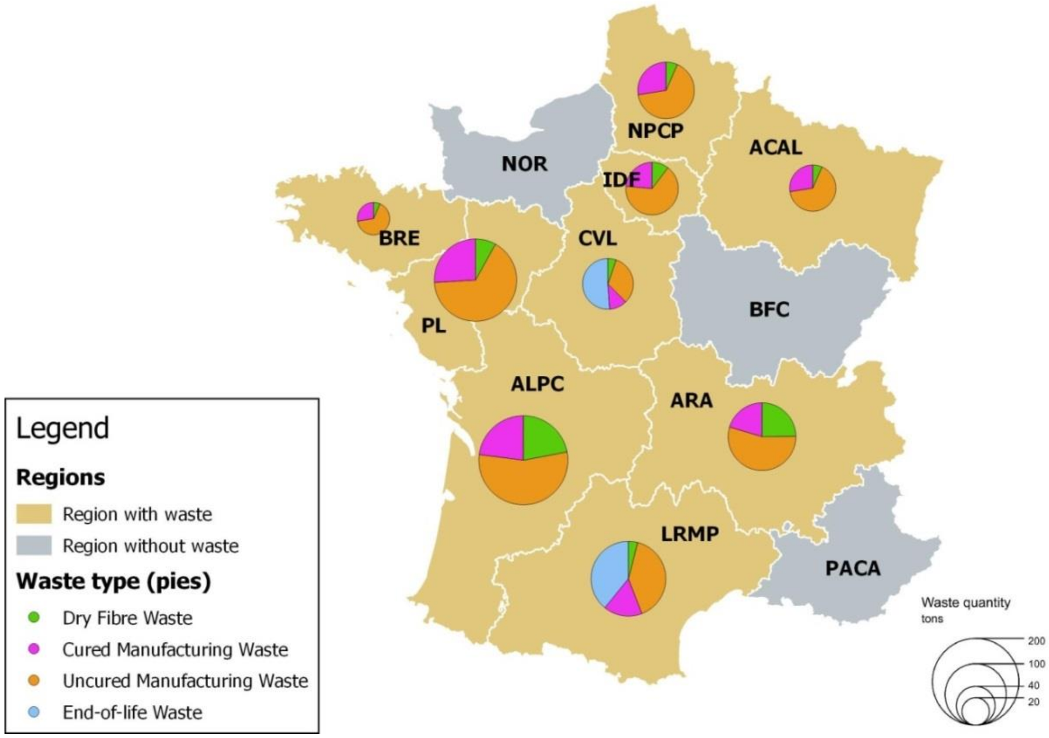


Figure 4-2: Snapshot of waste quantity in France (2016)

4.3.2. Waste treatment pathways

A classical Material Flow Analysis (MFA) methodology (Bringezu and Moriguchi, 2002) for determining the flow of materials and energy for all types of wastes based on cured production waste in all pathways has been developed. MFA of cured production in the studied paths and the characteristics of the modelled techniques are detailed in Chapter 3. For the other wastes, the following assumptions which are based on literature and the results of experts' interviews carried by Altran Research have been used:

- The MFA of all wastes in No-Fibre Recovery pathways (i.e. landfill, incineration, co-incineration) is the same.
- Dry Fibre waste is assumed to be shredded and does not need specific recycling technique for recovery. Its recycling yield is assumed to be 100 %.
- Because of uncured matrix, the uncured production waste has to be cured before going to grinding. Pyrolysis and supercritical water (SCW) process are assumed to accept this waste type.
- The MFA of cured and uncured in pyrolysis and SCW is assumed to be the same.
- Due to the possible presence of retardant flame additives in end-of-life waste, this waste type cannot go into the thermal techniques (i.e. incineration, co-incineration, and pyrolysis).

- In grinding and SCW, the necessary auxiliaries for end-of-life waste treatment are 2.8 times of the cured production waste with the same quantity of waste on considering its difficult recovery due to multiple layers. This assumption is generalised from the work on SCW experiments between cured production sample and aircraft piece of (Knight, 2013).

Besides, the costs of transport and treatment of No-Fibre Pathways of the uncured production waste are 1.5 times of the cured production waste because of the handling precaution for this hazardous waste.

4.3.3.7. Distribution of waste treatment echelon

The non-fibre recovery techniques are assumed to be available in all regions with a capacity at each region exceeding to the total wastes in the system. Currently, fibre recovery techniques have a limited presence in France with only three sites: (i) Bretagne (BRE), (ii) Auvergne-Rhône-Alpes (ARA) and (iii) Pays de la Loire (PL). BRE site have a capacity of over 1000 tonnes of chopped carbon fibre for grinding technique (Procotex, www.procotex.com). In another source (McConnell, 2010), this site is reported to involve pyrolysis. Therefore, in this model, a capacity of 1000 tonnes of waste input with 50 % in grinding and 50 % in pyrolysis is assumed. The ARA site uses grinding technique with capacity of 3000 tonnes (Halliwell, 2006). This site also works with other composites in reality, but we assume that its full capacity is available for carbon fibre waste in this study. SCW at pilot scale applied for carbon fibre recycling is found in the site in PL region (Oliveux et al., 2015a) and is assumed to have a capacity of 200 tonnes input per year. The location and the capacity of waste treatment techniques are summarised in Table 4-3.

Table 4-3: Location and capacity of waste treatment techniques

Waste treatment techniques	Availability	Capacity (tonnes/year)
Non-fibre recovery techniques (landfill, incineration, co-incineration)	All regions	unlimited
Grinding	BRE	500
	ARA	3000
Pyrolysis	BRE	500
Supercritical water (SCW)	PL	200

4.3.3. Transport echelon

In order to simplify the system, the CFRP waste management in this study uses the road mode of transport. All wastes have to be compressed at source before being transported to other regions for treatment. If the waste is treated at the origin region, the compression step is not necessary.

The lorry of 16-32 tonnes certified EURO5 is used to transport all wastes and recovered products in this model. The evaluation of GWP impacts from this activity is based on this type of vehicle. The transport price is a variable cost depending on waste/recovered products quantity and distance. This cost is estimated at 0.14 €/(t.km) (Schade et al., 2006) for all normal goods including non-hazardous wastes and recovered products. Considering the specific configuration for uncured waste which is classified as a hazardous waste, its transport cost is assumed to be 1.5 times than the standard cost.

To simplify the modelling, all waste sources and recycling sites in the same region are assumed to locate at the same location, therefore, only the inter-region transportation is considered in this study. The distances between regions which are estimated from the distances for the most rapid path of road transportation in Google Maps of their regional capitals, are detailed in Appendix 5.

4.3.4. Quality of recovered products and markets

The products recovered from the Fibre Recovery Pathways have diverse quality depending on the process. Moreover, the requirement of each market is different from the type of product and quality of products. In this study, the ratio of quality of recovered products over standard conventional products replaced by the equivalent recovered products, are used to represent the quality of products output and the so-called acceptability index of market. This assumed index is the minimum quality that recovered products must have to go into the corresponding market. There is no weight compensation to satisfy the quality requirement of replaced materials in market.

The retention of tensile strength in compared with virgin fibre is used to quantify the quality of recycled fibre. Its values are the average of the best quality of recycled fibre from the experiments of (Piñero-Hernanz et al., 2008a; Meyer et al., 2009; Akonda et al., 2012; Pimenta and Pinho, 2012; Greco et al., 2013; Stoeffler et al., 2013). The dry fibre is considered to conserve its quality after shredding. The other recovered products are assumed to have 100 % of quality of the replaced materials. The quality of all recovered products from the Fibre Recovery Pathways and the characterisation of markets are resumed in Appendix 4.

4.4. Results and Discussions

4.4.1. Pareto optimal solutions

The Pareto front (Figure 4-3) is constituted of 11 alternatives. Alternatives 1 and 11 refer to cost minimisation and GWP minimisation respectively. The convex form of Pareto front indicates that the two objective functions are conflicting, resulting from the effect of the avoided impacts included in the GWP function though both the cost and the GWP impacts of process activities (without the avoided impacts) have linear relationship with materials flows.

Figure 4-4 shows the evolution of waste treatment techniques used through the alternatives of Pareto front. Minimising the GWP impacts promotes the recovery pathways in general and the techniques with high value recovered products. From alternatives 1 to 11, the utilisation of landfill is reduced and replaced by incineration (2-3); this latter is also substituted more and more by grinding which loses gradually its part then favouring pyrolysis and SCW in the alternatives 5-11. This evolution corresponds to an increase in the avoided impacts released from incineration to grinding then to pyrolysis and SCW.

Instead of losing recoverable materials in landfill, waste can be valorised to electricity in incineration. The avoided impacts from substitution of energy produced in France are too low to compensate all impacts from the emissions of process. Although co-incineration is modelled with a similar process as for incineration, the reuse of its outputs in clinker production covers all GWP impacts from the process. However, due to its high cost, co-incineration which has negative GWP impacts cannot win over the other techniques. With the high values of recovered products, all fibre-recovery techniques have negative GWP impacts. The conventional production of carbon fibre emits very high GWP impacts. The avoided impacts from the replacement of carbon fibre in pyrolysis and SCW are much more important than limestone-glass fibre from grinding. Besides, as matrix is also valorised as a by-product in SCW, and this technique offers the lowest GWP impacts.

The Non-Fibre recovery pathways have an advantage in accessibility for waste treatment. They are assumed to be available at all regions with unlimited capacity. The Fibre recovery techniques are currently located in some regions and are limited in capacity. However, this advantage of the Non-Fibre recovery techniques has a low economic interest in the system. With the slight increase of unit cost per 1 kg of waste (0.0025 €/kg) in alternative 1 which has more than 50 % of waste in No-Fibre recovery technique (i.e. landfill), the GWP impacts of the system become negative in alternative 4 which recovers 99.6 % of waste with the reinforcement of grinding dominance. This technique has the lowest operation cost in Fibre recovery pathways. Furthermore, all wastes can be operated with grinding. SCW can treat all wastes but suffers from a high operation cost. In this case study, the use of a simple recycling technique like grinding, leads to 2.7 % increase in the minimum cost with avoiding the loss of 52.5 % of wastes in landfill. Grinding is therefore helpful to increase the recycling yield under the cost minimisation strategy. However, this technique suffers from a low value added of its recovered products on the market.

The capacity also influences on the distribution of techniques of Fibre recovery techniques. The total capacity of grinding is higher than the total waste quantity. However, pyrolysis and SCW have limited capacities. Although SCW has the lowest GWP impacts, this technique cannot yet dominate in the alternative 11 due to its capacity limitation. This alternative is also highlighted by the saturation of capacity for pyrolysis and SCW plants.

In this case study, all the recovered products are directly reused on the recycling plant sites for all the solutions found by the optimisation strategy. There is no distribution of products from plant to market because all markets present at the region of recycling plants. Without the limited demand constraints, the markets have no impacts on decision of waste distribution in upstream. This latter depends therefore on the characterisation of the waste treatment techniques.

The alternatives are ranked into this following order by the decision aid method M-TOPSIS with two objectives, i.e. cost minimisation and GWP minimisation: 6 > 7 > 5 > 8 > 4 > 9 > 10 > 3 > 11 > 2 > 1. The M-TOPSIS solution found is alternative 6.

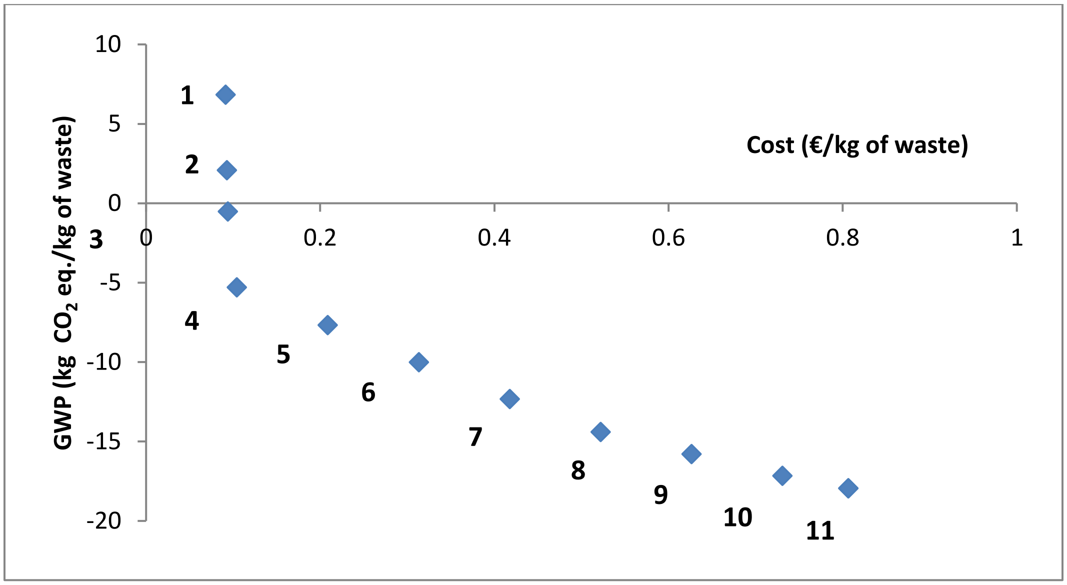


Figure 4-3: Pareto front of the case study

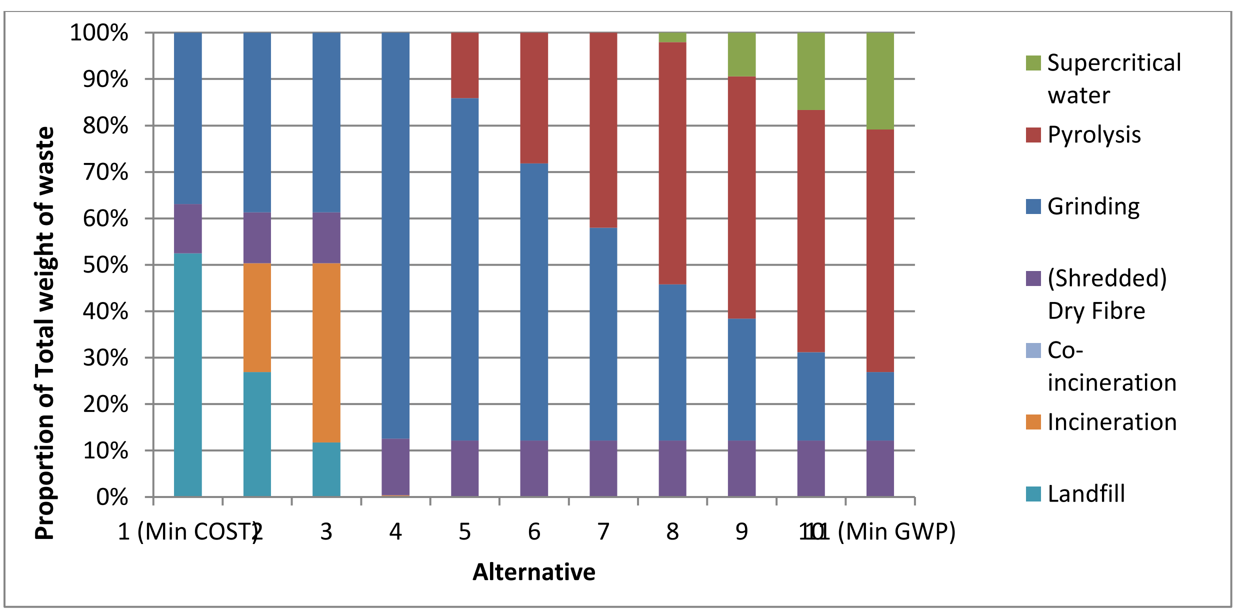


Figure 4-4: Distribution of waste treatment techniques in Pareto optimal solutions

4.4.2. Network configurations from bi-criteria optimisation

Figure 4-5 shows the waste distribution for each pathways corresponding to alternatives 1 (i.e. cost minimisation), 6 (i.e. M-TOPSIS choice), and 11 (i.e. GWP minimisation).

For cost minimisation (alternative 1), the model favours the two lowest cost techniques, i.e., landfill and grinding that can treat all kinds of waste. Although grinding exhibits the lowest cost among all the considered techniques with a total installed capacity superior to the global waste quantity, it is only located in two regions. The transport cost is main reason for switching to landfill. Landfilling turns out to the most competitive option compared to the other options apart from "in situ" grinding. Due to the diverse distribution of wastes, over 50 % of total wastes are landfilled on site to minimise cost while all the wastes located in the regions where grinding is present are recovered. Although dry fibre waste can be recovered by whatever the Fibre-recovery techniques by shredding, 12.7 % of this waste is lost in landfill due to the high distance from waste source to recycling plant. The SCW plant (only present in PL region) is used for curing the uncured waste generated "in situ" to reduce the transportation cost, and for shredding the dry fibre waste on site or coming from neighbouring regions (Figure 4-6 (a)).

However, in order to minimise GWP impacts, the configuration of network found by the optimisation strategy is balanced by the GWP impacts from operation activities, the avoided GWP impacts from recovered products and the capacity of techniques. Since the impacts of the recovered products from Fibre-Recovery pathways are much more important than both the impacts of activities and the impacts from No-Fibre Recovery Pathways, the first options are favoured so as to avoid the maximum GWP as possible. This explains why this situation leads to a saturation of both pyrolysis and SCW plants. But the total capacity of these two plants cannot take into account all the wastes apart from dry fibre which does not depend on recycling capacity but on pre-treatment capacity at recycling plant. Grinding is mainly used for EOL waste treatment. Besides grinding, this waste can be recovered by only SCW (pyrolysis is not allowed). In each process, the treatment of EOL waste needs more auxiliaries input than of the other wastes. This waste also contributes to the lowest part in the total wastes quantity in the system. Therefore, EOL grinding allows saving capacity of pyrolysis and SCW for cured and uncured production wastes on reducing the GWP impacts produced from EOL treatment. As the GWP criterion does not consider the difference in transport between non-hazardous waste and hazardous waste transport like the cost. The uncured waste is directly transported to recycling plant without pre-treatment at source before transportation in alternative 11 (Figure 4-6 (c))

Alternative 6 is the top-ranked solution obtained by M-TOPSIS. As mentioned before, there is slightly small gap in cost between the cheapest No-Fibre recovery technique, i.e. landfill and the cheapest Fibre recovery technique, i.e. grinding; however, the difference in GWP impacts between the two pathways is very high due to the value of recovered products. Although all wastes go to Fibre-recovery pathways like the alternative 11, there are fewer flows of waste transported to recycling sites in the alternative 6. The wastes which are not at the regions of recycling plant are transported to the closest region. However, SCW is not applied in this alternative due to the high operational cost of SCW compared to grinding and pyrolysis. The avoided GWP impacts from the reuse of oligomers as phenol are not high enough to balance the GWP impacts and the high cost from recycling operation so that SCW can compete with pyrolysis. In this context, curing the uncured waste at SCW plant (PL region) before grinding this waste at BRE region is needed to reduce the transportation cost in alternative 6 as the network in alternative 1 with a lower quantity of uncured waste. This SCW is also used for shredding the dry fibre on site or from the neighbouring regions (Figure 4-6 (b)).

In this case study considered, all the markets exist at the regions where recycling is implemented. Therefore, all the recovered products generated from the recycling plants depend on upstream. Yet, the distribution of products can help developing potential markets where the accumulation of products is generated, so that the upstream waste management can be developed in order to solve the treatment of all wastes on the one hand and the valorisation of recovered products from waste on the other hand.

The snapshots of the amount of recovered products from Fibre-Recovery pathways are shown in Figure 4-7 for (a) alternative 1, (b) alternative 6, and (c) alternative 11. It can be seen that the distribution of recovered products, which results from upstream waste distribution varies with the strategy of the system. The fibre market is not well developed in alternative 1 because of a high contribution of landfilling, whereas pyrolysis and SCW are strongly involved in alternative 11 with strong fibre market. The markets for products of grinding, i.e. powder and fibrous fractions are well represented in alternatives 1 and 6, but poorly contribute in alternative 11. Beside fibre market, the use of SCW needs the existence of market for its by-product, i.e., oligomers.

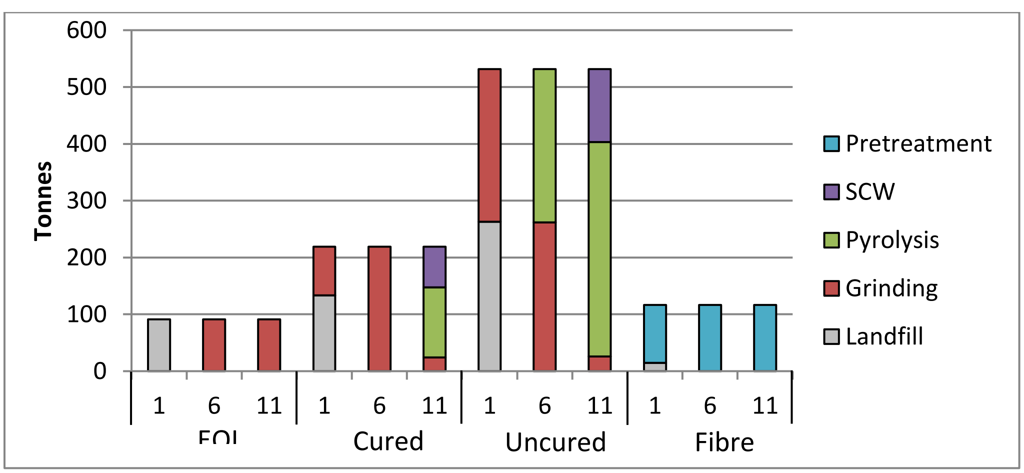
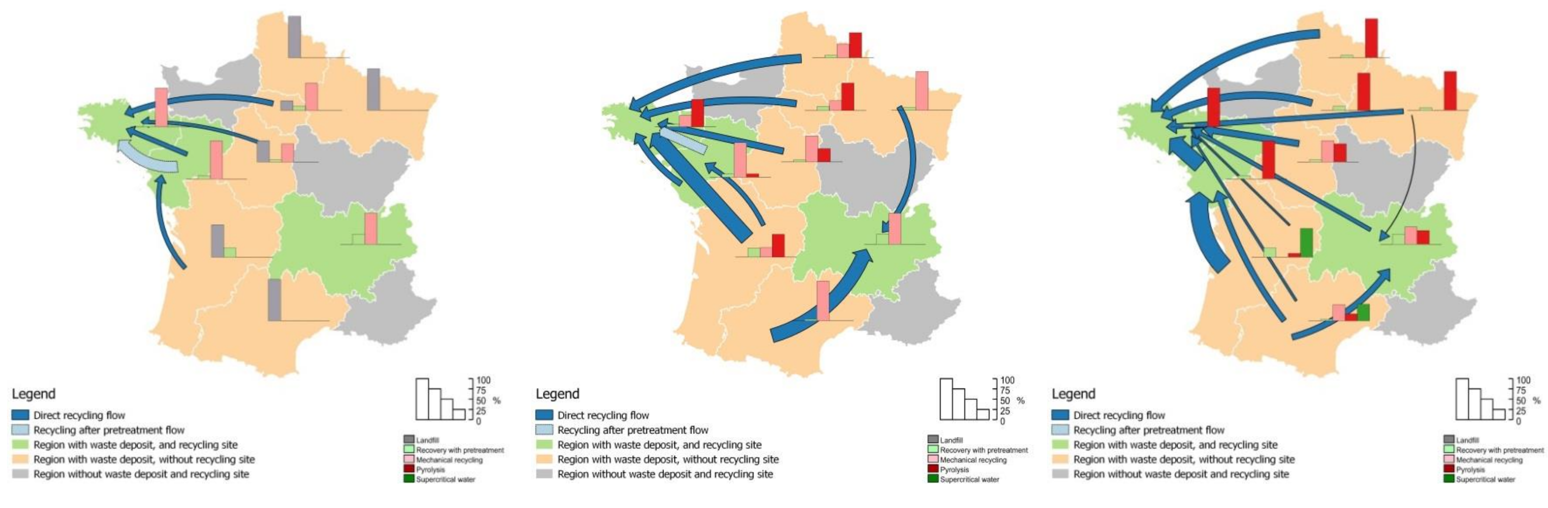
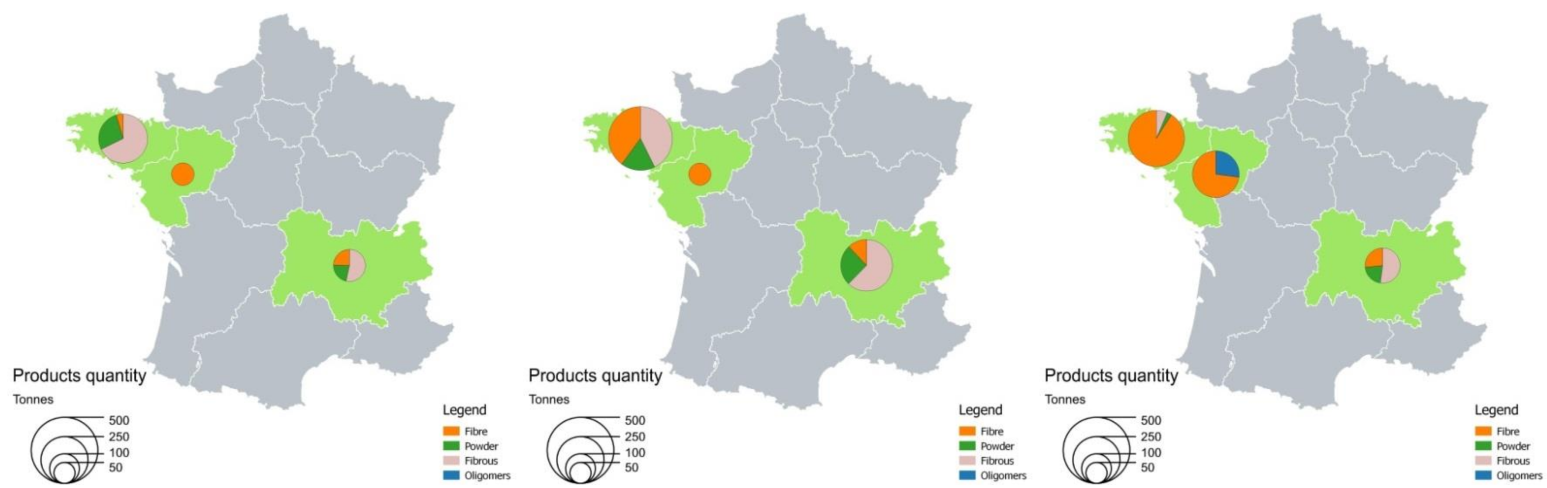


Figure 4-5: Distribution of waste type in waste treatement pathways



(a) (b) (c)

Figure 4-6: Waste flows and waste distribution in each region of, (a) alternative 1, (b) alternative 6, (c) alternative 11



(a) (b) (c)

Figure 4-7: Snapshot of recovered products from Fibre-Recovery pathways of, (a) alternative 1, (b) alternative 6, (c) alternative 11

4.4.3. Extension of recycling capacity

Not surprisingly, the results obtained show the importance of recycling capacity in waste distribution, e.g. the saturation of pyrolysis and SCW in the solution for GWP impacts minimisation. In this section, the recycling capacity constraint is relaxed by the extension of recycling capacity in order to determine the necessary capacity of each plant, i.e. so that the total waste amount of the system can be treated.

The same formulation as the one used for the base case study with ε-constraint method and lexicographic technique, is involved: in this case, the Pareto front (Figure 4-8) is constituted of 18 alternatives (numbered from 1 to 18 with decreasing GWP impact). Alternatives 1 and 18 are the solutions of lexicographic technique with priority of cost minimisation and GWP minimisation respectively.

The same formulation as the one used for the base case study with ε-constraint method and lexicographic technique, is involved: in this case, the Pareto front (Figure 4-8) is constituted of 18 alternatives (numbered from 1 to 18 with decreasing GWP impact). Alternatives 1 and 18 are the solutions of lexicographic technique with priority of cost minimisation and GWP minimisation respectively. Figure 4-9 shows the waste distributions for the solutions of the Pareto front. Alternative 7 is the M-TOPSIS solution for the bi-criteria optimisation problem in the case of the extension of recycling capacity.

The evolution of waste distribution exhibits the same trend for the solution of cost minimisation and of GWP minimisation respectively as in the base case study. The low cost option with low value of recovered products is substituted by the higher cost option with higher value of recovered products. The effect of extension of recycling capacity can be seen clearly by the total dominance of SCW in the system for GWP minimisation. In the base case study, the system is trapped by the limitation of capacity for both pyrolysis and SCW. The GWP impacts are reduced of 20 % while the cost is doubled in the case of extension of recycling capacity in comparison with the base case for the same strategy of GWP minimisation. This situation can be explained by the high operation cost, and by-product recovery of SCW. The impacts of SCW can be confirmed by the deviation of the slope from alternatives 4-9 which do not use SCW to alternatives 10-18 which include SCW in the system. The capacity of grinding in this base case study is high enough to treat all waste input flows in order to achieve the lowest cost in the system. The configuration for cost minimisation strategy with capacity extension is therefore the same as the base case study.

The total waste flows input in recycling plant for alternatives 1, 7 and 18 are shown in Table 4-4. The wastes volume in pre-treatment of all recycling plant is not changed between the alternatives 7 and 18 because of the optimal distribution of dry fibre waste and no pre-treatment for uncured waste before transportation to recycling site. However, under the objective of cost minimisation (alternative 1), pretreatment part of PL plant has to additionally treat the uncured waste of the region for curing before grinding of this waste at BRE in order to reduce the transportation cost. In this alternative, only grinding plants operate, mainly in BRE and for a small quantity of ARA. However, in alternative 7, the waste flows input to ARA are tripled, and a small quantity of waste goes into grinding in BRE; more than half of total wastes are treated by pyrolysis in BRE. Otherwise, all wastes apart from dry fibre are recovered by SCW in PL in alternative 18. This plant has to recycle over 800 tonnes of wastes though there is no waste treated by SCW technique in the alternatives 1 and 7. With the 3 centres of recycling in BRE, PL and ARA regions, a high concentration of recycling activities in BRE and PL is observed due to the high quantity of wastes around these regions and the multiple recycling techniques in BRE and PL. Grinding in ARA region may be interesting in a solution in which both economic and environmental criteria are taken into account like alternative 7 or in the case with the solid market for recovered products of grinding around this region.

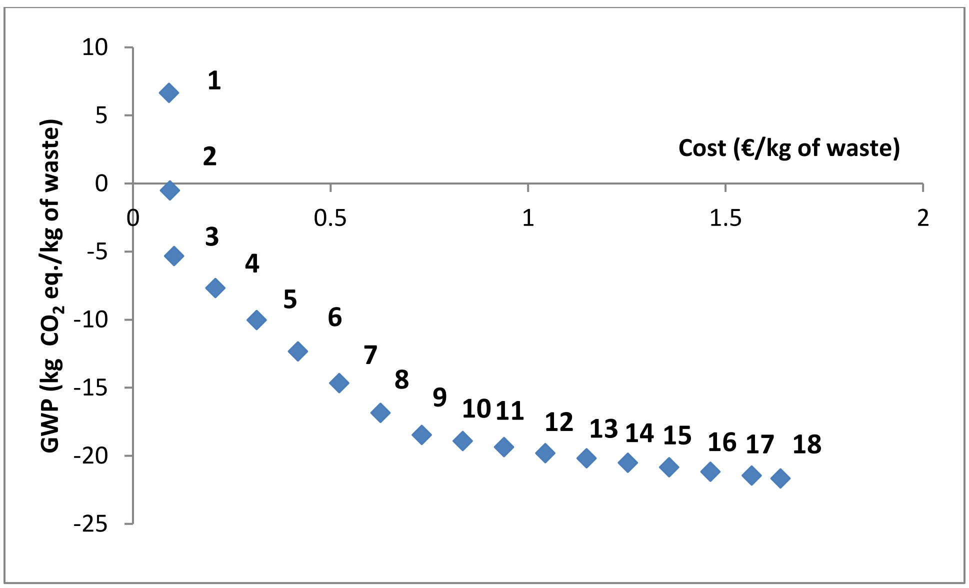


Figure 4-8: Pareto front of the case extended recycling capacity

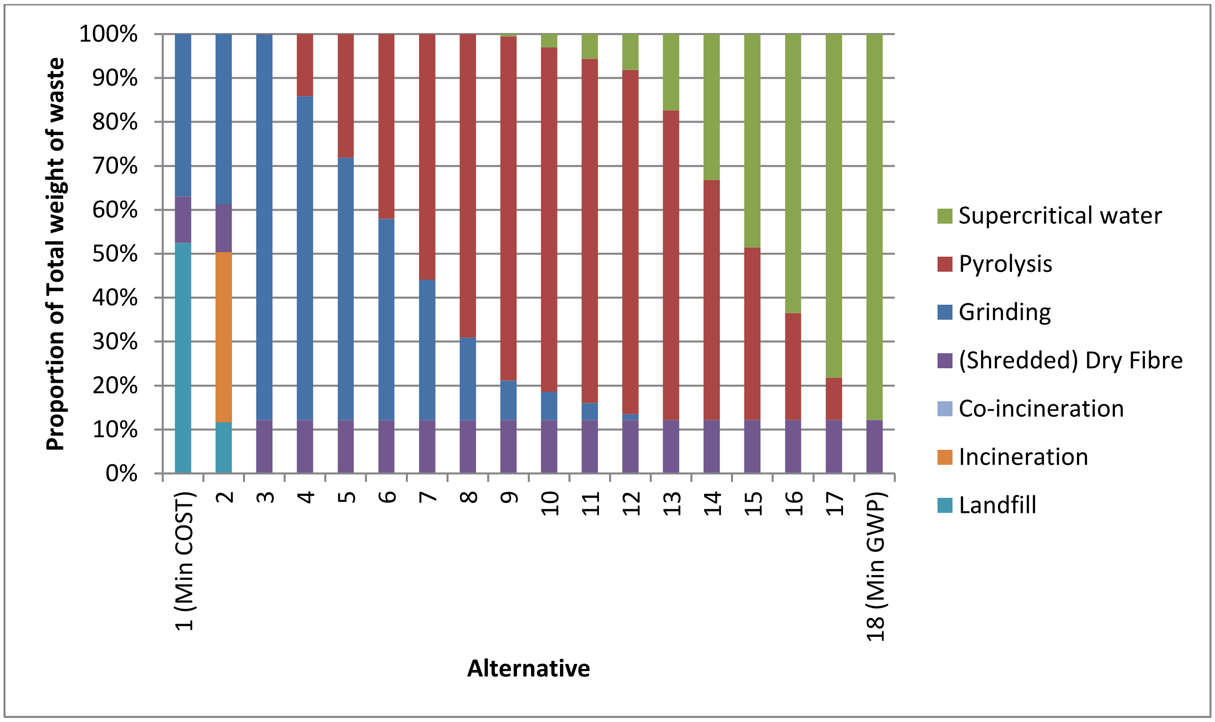


Figure 4-9: Distribution of waste treatment techniques in Pareto optimal solutions of the case extended recycling capacity

Table 4-4: Waste distribution of Fibre-recovery pathways in each region (the number of the alternative is in bold characters)

Amount of waste	Pre-treatment			Grinding			Pyrolysis			SCW		
(Tonnes)	1	7	18	1	7	18	1	7	18	1	7	18
BRE	13	18	18	264	38	0	0	522	0	0	0	0
PL	176	59	59	0	0	0	0	0	0	0	0	841
ARA	30	39	39	90	281	0	0	0	0	0	0	0

4.5. Conclusion

The increasing use of CFRP in aerospace leads to diverse and high quantity of wastes that will continue to grow in the future. Although the production of carbon fibre is expensive and polluting, the majority of wastes go to disposal routes like landfill or incineration for economic reason. However, with the progress in studies of recycling processes, carbon fibre recycling techniques have become new options for CFRP waste treatment with the conventional disposal paths. It is thus important to develop an optimised network for CFRP waste management dealing with the range of waste types and waste treatment techniques.

In this work, a linear model based on mathematical programming for aerospace CFRP waste management from upstream source to treatment and to downstream market is developed. A bi-criteria optimisation approach is proposed based on simultaneous cost and GWP impact minimisation. Cost evaluation includes all activities in the network, i.e. waste collection, pre-treatment, recycling process, product distribution.

Beside the impacts from activities, the value of recovered products is taken into account in GWP impacts via the avoided impacts. The model is applied to case study for determining the distribution of wastes in aerospace carbon fibre chain in France.

The results of the case study show the conflicting aspect between cost and GWP impacts. The decrease in GWP impacts can lead to an increase in the cost in the system. The waste distribution among the different treatment options depends on waste type, treatment technique (input, output, capacity, and operation conditions), and transport. The Fibre-recovery pathways are favoured for minimising GWP impacts to obtain higher avoided impacts than those obtained with the No-Fibre recovery pathways. Furthermore, these options do not have an economic advantage with the current cost in comparison with the operation cost of Fibre-recovery pathways. However, due to the centralisation of recycling plants, the wastes in the regions that are far from recycling plants are landfilled instead of being recovered by grinding technique, though grinding cost is lower than landfill fees in this case study in order to minimise the cost of system. An additional pre-treatment capacity besides recycling capacity is an essential strategy to save recycling capacity from recovery of dry fibre scrap for other wastes and to reduce the transportation cost of uncured waste by curing on site before transportation to other techniques. The combination of different techniques allows obtaining the compromise values of cost and GWP impacts in the system. Moreover, in system downstream, with the lack of quantitative data of markets for recovered products, this model allows flexible control under the qualitative data of markets presence in order to determine the volume of products valorised by recycling routes and to then develop potential markets where the accumulations of products is generated.

CHAPTER 5

A multi-period optimisation approach for deployment and optimal design CFRP waste supply chain

Abstract

A multi-period approach is developed in this chapter in order to study the impact of waste evolution for CFRP waste management in aerospace industry. In this model, the deployment of new recycling sites is established through MILP approach. The system is optimised by a bi-criteria optimisation including an economic objective (cost minimisation and NPV maximisation) and an environmental one (minimisation of GWP impacts). The potential for economic acceptability of recycled carbon fibres is assessed through the average prices calculated from the total cost and the profitability via NPV with a range of various fixed prices which represent different markets. The results show that the compromise strategy for both economic and environmental objectives lead to centralised configurations at the regions which are close to the important waste sources. The cooperation in the recovery system is needed to minimise cost and maximise profit. The improvement of recycling technology permits to achieve the compromise solution for both economic and environmental objectives. The estimation of waste evolution is a key point to design the system of waste management.

Résumé

Une approche multi-période est développée dans ce chapitre afin d'étudier l'impact de l'évolution des déchets au cours du temps pour la gestion des déchets de CFRP aéronautiques. Dans ce modèle, le déploiement de nouveaux sites de recyclage est établi par une approche MILP. Le système prenant en compte une variation dynamique de la quantité de déchets est modélisée et optimisé par une optimisation bi-critère incluant un objectif économique (minimisation des coûts et maximisation de la Valeur Actuelle Nette, VAN) et un objectif environnemental (minimisation du GWP). Le potentiel de l'acceptabilité économique des fibres de carbone recyclées est étudié à partir de prix moyens de fibres recyclées, calculés à partir du coût total et du critère de rentabilité de type VAN avec une gamme de différents prix sur des différents marchés. Les résultats montrent que la stratégie de compromis pour les objectifs économiques et environnementaux conduit à configuration centralisée dans des régions qui sont proches de sources de déchets importants. La coopération dans le système de recyclage est nécessaire pour minimiser les coûts et maximiser les profits. L'amélioration de la technologie de recyclage permet d'atteindre la solution de compromis pour les objectifs économiques et environnementaux. L'estimation de l'évolution des déchets est un point clé pour la conception du système de gestion des déchets.

Nomenclature

Indices/Sets:

$c \in \mathscr{C}, \mathscr{C} = \begin{Bmatrix} \text{Market 1,Market 2,} \\ \text{Market 3,Market 4} \end{Bmatrix}$	Market of Recovered Product
$e \in \mathscr{E}, \mathscr{E} = \{\text{Landfill,Incineration,Co-incineration}\}$	No-fibre Recovery Pathways
$i \in \mathscr{I}, \mathscr{I} = \{\text{Cured and chopped composite}\}$	Intermediate product
$l, l' \in \mathscr{L}, \mathscr{L} = \begin{Bmatrix} \text{NPCP,NOR,BRE,} \\ \text{ACAL,IDF,PL,CVL,} \\ \text{BFC,ALPC,ARA,} \\ \text{LRMP,PACA} \end{Bmatrix}$	Location/region
$p \in \mathscr{P}, \mathscr{P} = \{\text{Powdered,Fibrous,Fibre,Oligomers}\}$	Recovered Product from Fibre Recycling Technique
$r \in \mathscr{R}, \mathscr{R} = \begin{Bmatrix} \text{grinding,pyrolysis,} \\ \text{SCW,microwave} \end{Bmatrix}$	Fibre recycling technique
$s \in \mathscr{S}$ ($\mathscr{S} = \{\text{small,medium,large}\}$)	Plant scale
$t \in \mathscr{T}, \mathscr{T} = [0;20] \subset \mathbb{N}$	Year
$w \in \mathscr{W}, \mathscr{W} = \begin{Bmatrix} \text{dry fibre, uncured production,} \\ \text{cured production, EOL} \end{Bmatrix}$	Waste type

Parameters:

$CAPEL_{el}$	Capacity of no-fibre recovery technique ***e*** at region ***l***, (tonnes of waste/year)
$CAPR0_{rs}$	Standard maximum recycling capacity of deployed recovery of technique ***r*** at scale ***s***
$CAPROL_{rl}$	Recycling capacity of the existing recovery site of technique ***r*** at region ***l***, (tonnes of waste/year)
CQL_{cp}	Minimum quality of product ***p*** accepted by sector ***c*** (%)
$DIST_{ll'}$	Distance between region ***l*** and region ***l'***, (km)

ECOM	Energy for compression (kWh/tonne)
EPR_w	Energy used for pre-treatment of waste ***w*** (kwh/tonne)
GWPE	GWP impacts of electricity (tonnes CO_2 eq./MJ)
$GWPNRAU_{we}$	Avoided GWP impact of no-fibre recovery pathway ***e*** from waste ***w*** (tonnes CO_2 eq./tonne of waste)
$GWPNRU_e$	GWP impacts of treatment by no-fibre recovery pathway ***e*** (tonnes CO_2 eq./tonne of waste)
$GWPP_p$	GWP impacts of conventional production of product ***p*** (tonnes CO_2 eq./tonne of product)
GWPTRU	GWP impacts of transport (tonnes CO_2 eq./tkm)
$GWPWR_{rw}$	GWP impacts of treatment of waste ***w*** by fibre recycling technique ***r*** (tonnes CO_2 eq./tonne of waste)
$INV0_{rs}$	Unit investment cost for a deployed recovery site of technique ***r*** at scale ***s*** (€)
$OCOST_{rs}$	Other direct cost (labour, maintenance) of deployed recovery site ***r*** at scale ***s*** (€/year)
PCOM	Cost of compression (€/tonne)
PE	Unit cost of electricity (€/kWh)
PIR_{ri}	Unit cost of treatment of recycling technique ***r*** for intermediate product ***i*** (€/tonne)
PNR_{ew}	Unit cost of no-fibre recovery technique ***e*** for waste ***w*** (€/tonne)
PP_p	Price of recovered product ***p*** (€/tonne)
$PSTW_w$	Unit cost of waste storage (€/tonne of waste)
PTR0	Cost of normal transport for recovered product (same for all type product p) (€/tkm)
PTR_w	Cost of transport for waste ***w*** (€/tkm)
PWR_{rw}	Unit cost of treatment of recycling technique ***r*** for waste ***w*** (€/tonne)
$QLPRP_{wp}$	Quality of recovered product ***p*** from waste ***w*** by pretreatment (%)
$QLRPI_{irp}$	Quality of recovered product ***p*** from intermediate ***i*** by recycling technique ***r*** (%)
$QLRPW_{wrp}$	Quality of recovered product ***p*** from waste ***w*** by recycling technique ***r*** (%)
QW_{wtl}	Waste quantity ***w*** generated at region ***l*** at year ***t***, (tonnes of waste)
$RIRP_{rpi}$	Conversion ratio from intermediate product ***i*** to final product ***p*** by fibre recycling technique ***r*** (%)
RNR_e	Revenue from no-fibre recovery pathway ***e*** (€/tonne of waste)
$RWRP_{rpw}$	Conversion ratio from waste ***w*** to final product ***p*** by fibre recycling technique ***r*** (%)
XDP_{cpl}	Index of existence of sector ***c*** for product ***p*** at region ***l***
XIR_{ir}	Acceptance index of fibre recycling technique ***r*** for intermediate product ***i***, 1 if the

	technique ***r*** can treat the intermediate product ***i***, 0 otherwise
$XPRP_{wp}$	Conversion rate of waste ***w*** to product ***p*** after pretreatment
XPR_{w}	Index for waste ***w*** which does not need recycling process after pretreatment step for recovery, 1 if the waste ***w*** does not go to the recycling process for recovery, 0 otherwise
$XTR_{ll'}$	Factor of transport, 1 if two regions (***l*** and ***l'***) are different; 0 otherwise
XWI_{wi}	Index of conversion waste ***w*** to intermediate product ***i*** after pretreatment
$XWNR_{we}$	Acceptance index of no-fibre recovery technique ***e*** for waste ***w***, 1 if the technique ***e*** can treat the waste ***w***, 0 otherwise
$XWPR_{w}$	Index for waste ***w*** which can go to pre-treatment step separately from recycling process, 1 if the separated pretreatment step is opened for the waste ***w***, 0 otherwise
XWR_{wr}	Acceptance index of fibre recycling technique ***r*** for waste ***w***, 1 if the technique ***r*** can treat the waste ***w***, 0 otherwise
ω	Ratio of maximum storage capacity to maximum recycling capacity at a deployed recovery site

<u>Continuous variables:</u>

$FIIR_{irtll'}$	Flow of intermediate product ***i*** transported from pretreatment deployed site at ***l*** to deployed recycling site of technique ***r*** at ***l'*** in year ***t***, (tonnes)
$FIOR_{irtll'}$	Flow of intermediate product ***i*** transported from pretreatment existing site at ***l*** to existing recycling site of technique ***r*** at ***l'*** in year ***t***, (tonnes)
$FPIDR_{wrpctll'}$	Flow of product ***p*** recovered from waste ***w*** by direct recycling from deployed recovery site of technique ***r*** at ***l*** and then distributed to market ***c*** at ***l'*** in year ***t***, (tonnes)
$FPIIR_{irpctll'}$	Flow of product ***p*** recovered from ***i*** by deployed recovery site of technique ***r*** at ***l*** and then distributed to market ***c*** at ***l'*** in year ***t***, (tonnes)
$FPIPR_{wrpctll'}$	Flow of product ***p*** obtained from pretreatment of waste ***w*** by deployed recovery site of technique ***r*** at ***l*** and then distributed to market ***c*** at ***l'*** in year ***t***, (tonnes)
$FPODR_{wrpctll'}$	Flow of product ***p*** recovered from waste ***w*** by direct recycling from existing recovery site of technique ***r*** at ***l*** and then distributed to market ***c*** at ***l'*** in year ***t***, (tonnes)
$FPOIR_{irpctll'}$	Flow of product ***p*** recovered from ***i*** by existing recovery site of technique ***r*** at ***l*** and then distributed to market ***c*** at ***l'*** in year ***t***, (tonnes)
$FPOPR_{wrpctll'}$	Flow of product ***p*** obtained from pretreatment of waste ***w*** by existing recovery site of technique ***r*** at ***l*** and then distributed to market ***c*** at ***l'*** in year ***t*** (tonnes)
$FWNR_{wetl}$	Flow of waste ***w*** to no-fibre recovery technique ***e*** in year ***t*** at region ***l***, (tonnes)
$FWRIDR_{wrtl}$	Flow of waste ***w*** for directly recovery at deployed recycling site of technique ***r*** at ***l*** in year ***t***, (tonnes)
$FWRIPR_{wrtl}$	Flow of waste ***w*** for pretreatment at deployed site of technique ***r*** at ***l*** in year ***t***, (tonnes)
$FWRI_{wrtll'}$	Flow of waste ***w*** from waste source ***l*** transported directly to deployed recycling

	site of technique ***r*** at ***l'*** in year *t*, (tonnes)
$FWRODR_{wrtl}$	Flow of waste ***w*** for directly recovery at existing recycling site of technique ***r*** at ***l*** in year ***t***, (tonnes)
$FWROPR_{wrtl}$	Flow of waste ***w*** for pretreatment at existing site of technique ***r*** at ***l*** in year ***t***, (tonnes)
$FWRO_{wrtll'}$	Flow of waste ***w*** from waste source ***l*** transported directly to existing recycling site of technique ***r*** at ***l'*** in year ***t***, (tonnes)
$QWRS_{wrtl}$	Quantity of waste ***w*** stored at a deployed recycling site ***r*** in year ***t*** at region ***l***, (tonnes)
$YRSTL_{rstl}$	Binary variable for implementation of new recycling site of technique ***r*** at scale ***s*** in year ***t*** at region ***l***

5.1. Introduction

In the previous chapter, a model that allows modelling and optimising the aerospace CFRP waste supply chain has been developed with a mono-period approach. The results obtained have highlighted the full conflict between economic (minimisation of total cost) and environmental (minimisation of GWP impact) criteria in the static model. If Recovery pathways can be intuitively found more interesting in order to minimise GWP impact to obtain higher avoided impacts from a qualitative viewpoint than those from Non Recovery pathway, the use of the model is particularly relevant to design the supply chain (number, type, size and location of treatment processes as well as storage and distribution units). However, considering an economic objective, a priority is given to landfilling to reduce the transport cost due to the centralised recycling system.

A multi-period approach is developed in this chapter in order to overcome this duality and to propose a more realistic model for the deployment phase. Indeed, regarding the evolution of composites in commercial airplanes and the high increase in their production over time (See **General Introduction**), a multi-period approach is needed for CFRP waste management in aerospace industry. In this approach, the creation of new recycling sites in appropriate regions and the variation of waste quantity through years are also taken into account.

The aim of this chapter is to model and design the configuration of CFRP waste management encompassing dynamic variation of waste quantity by a bi-criteria optimisation including economic objective and environmental objectives. However, the price of recycled carbon fibres is hard to estimate according to the targeted application. Indeed, as the market of recycled carbon fibres is not mature yet, carbon fibres are generally used to substitute other cheaper fibres, such as glass fibres in SMC and BMC. But the recent advance on recycling and conditioning techniques can spread the use of recycled carbon fibres in higher value applications in parallel with a fibre market that is expected to expand significantly in the coming years. Therefore, in order to study the potential economic profit of recycled carbon fibre, a two-stage economic strategy is taken into account via cost minimisation on the one hand and Net Present Value maximisation on the other hand: cost minimisation is carried out to determine the range of prices for recovered fibres while the maximisation of Net Present Value is considered to study the profitability of the waste management project at the end of the horizon time.

This chapter is organised into 5 sections. Section 5.2 describes the strategy of modelling and optimisation. The scenarios of waste evolution and the framework of optimisation are also presented. The system considered and its mathematical model with the associated constraints and objective functions are developed in Section 5.3. The results obtained from the implementation of consecutive steps of the optimisation process are presented in Section 5.4, firstly with an overview of the optimisation of existing capacity, and secondly with emphasis on the analysis of a bi-criteria optimisation based on COST-GWP and on NPV-GWP respectively. Lastly, some conclusions and perspectives will be drawn in Section 5.5.

5.2. Methodology

5.2.1. Scenarios for wastes evolution

Forecasting the evolution of wastes is a crucial point for the model because it will allow defining the need to create new recycling sites. Indeed, the end-of life CFRP waste is expected to highly increase within 20 to 30 years due to the retirement of the recent high CFRP-content models. Moreover, aerospace CFRP production wastes have been increasing with the high productivity of aircraft manufacturing to fill important order backlogs.

It is important to highlight that the scenarios of waste evolution lie on several estimations for the aerospace carbon fibre sector in the context of France. A 20-year horizon time (2016 – 2035) is involved and 2016 is settled as the first year of the study.

The first scenario is qualified as “Business as usual” (BAU) and represents the scenario where the quantity of wastes for the first year is constant over the years. Although non-realistic, this scenario serves as a reference compared to the other scenarios considered. Besides BAU, different waste scenarios are developed: the production wastes have been varied by an annual variation rate (**δ**) according relation (5.0); the end-of-life waste is estimated similarly to the assumptions made in chapter 4 and based on the delivered aircraft from 1991 to 2010 which are projected for retired aircraft from 2016 to 2035 over a 25-year lifespan of airplane.

$$QW_{\substack{t\in\mathscr{T}\\ l\in\mathscr{L}\\ w\in\mathscr{W}\setminus\{EOL\}}} = QW_{\substack{t=1\\ l\in\mathscr{L}\\ w\in\mathscr{W}\setminus\{EOL\}}} \times (1+\delta)^{t-1} \qquad (5.0)$$

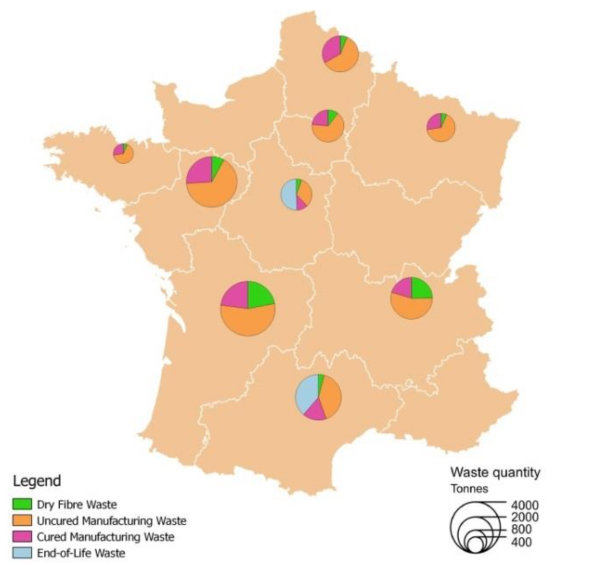
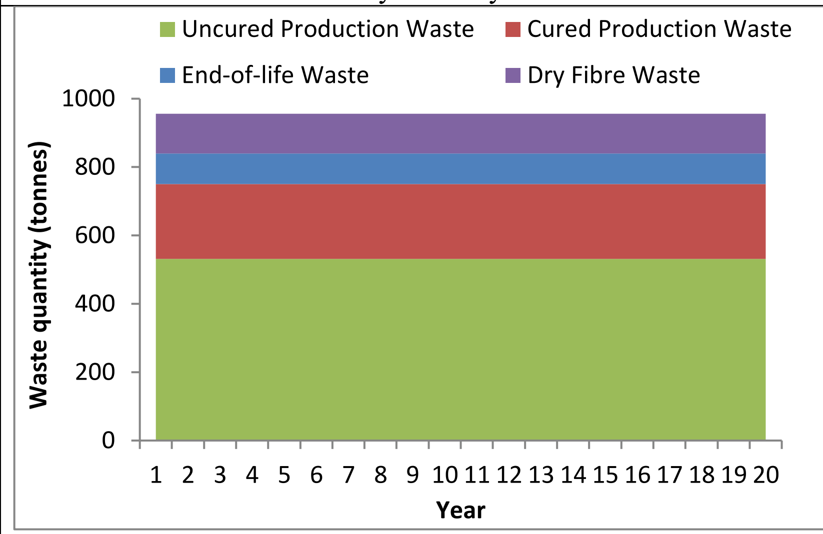
The CFRP composition of aircraft models and their deliveries from 1991 to 2010 can be found in Appendices 1 and 2.

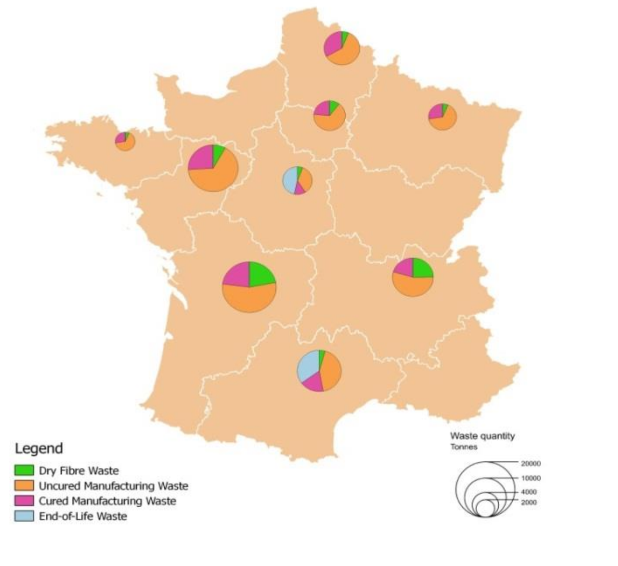
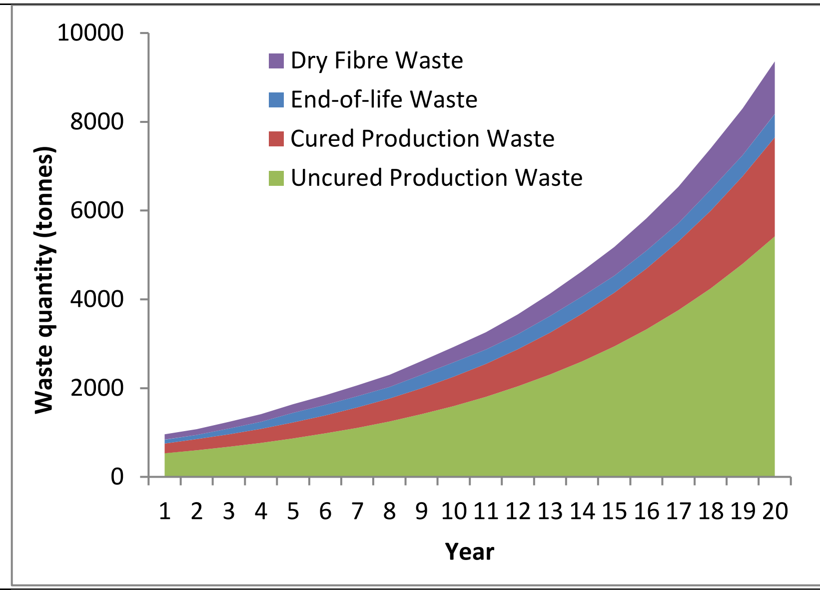
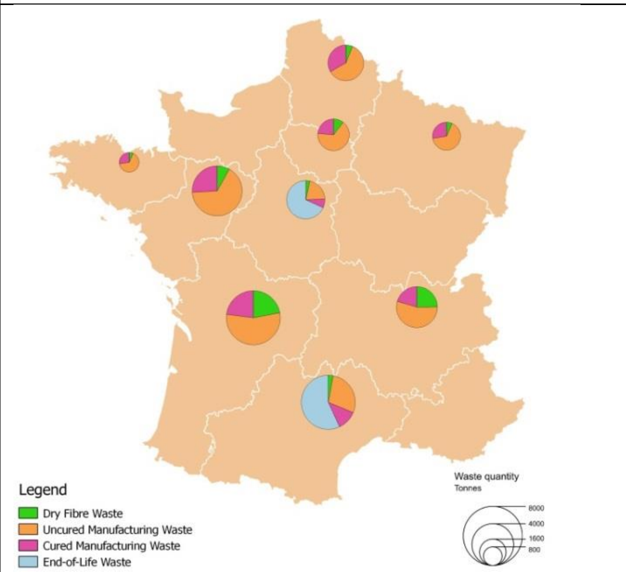
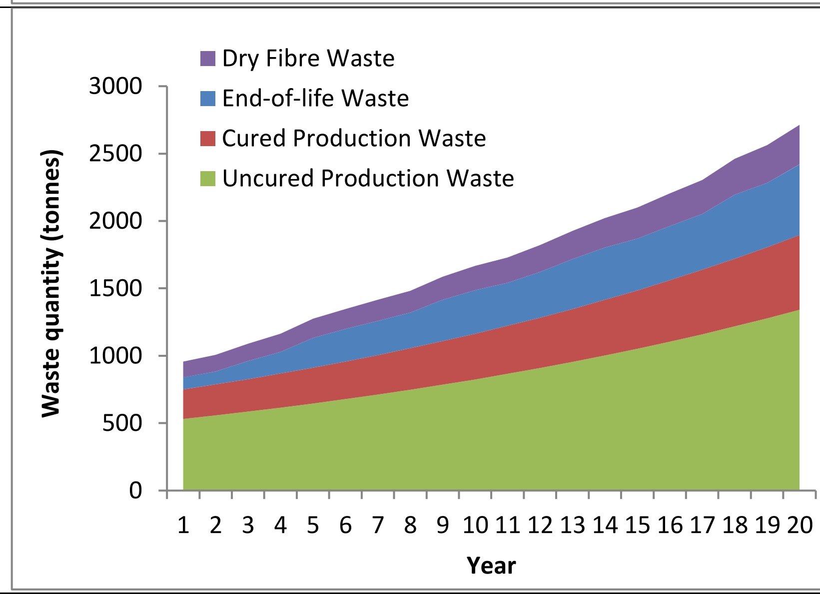
To our knowledge, the prediction of the temporal evolution of production wastes has not been reported in the dedicated literature. In this work, their estimation has therefore been based from the prediction of production capacity and demand concerning the Aerospace Sector. Two scenarios of evolution of production waste will be studied considering an increasing and decreasing evolution, respectively and for each trend, two extreme cases are modelled, either a strong or a light evolution.

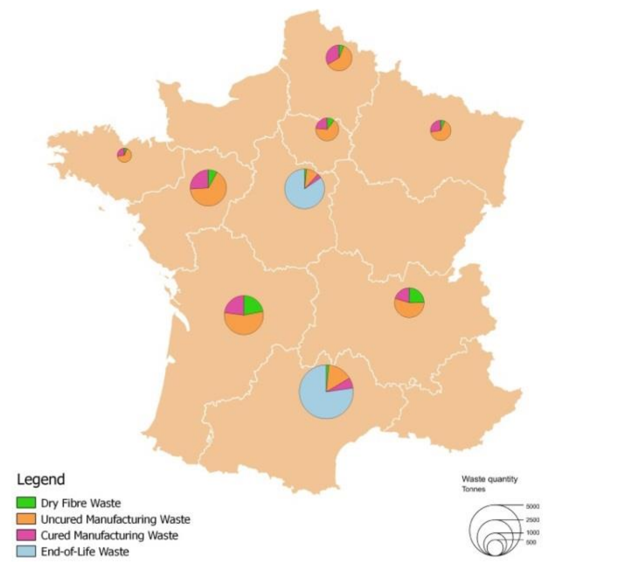
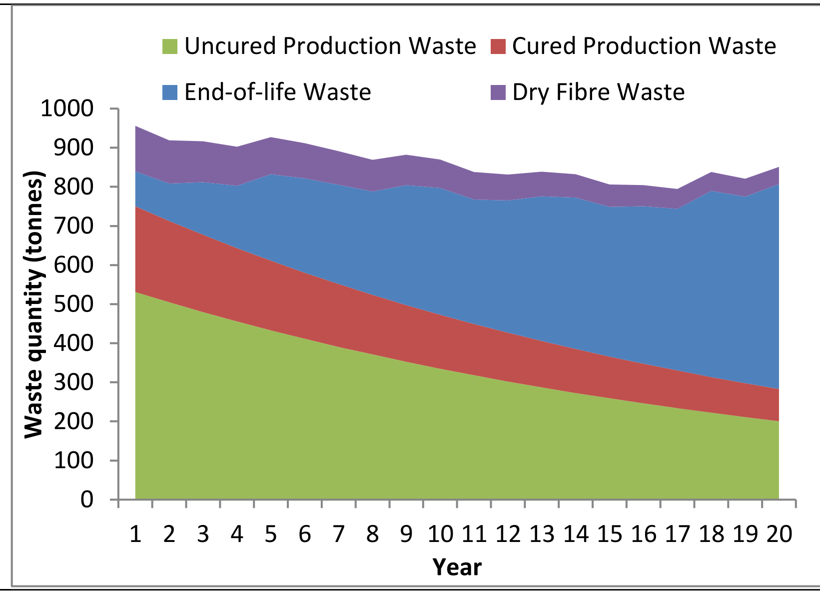
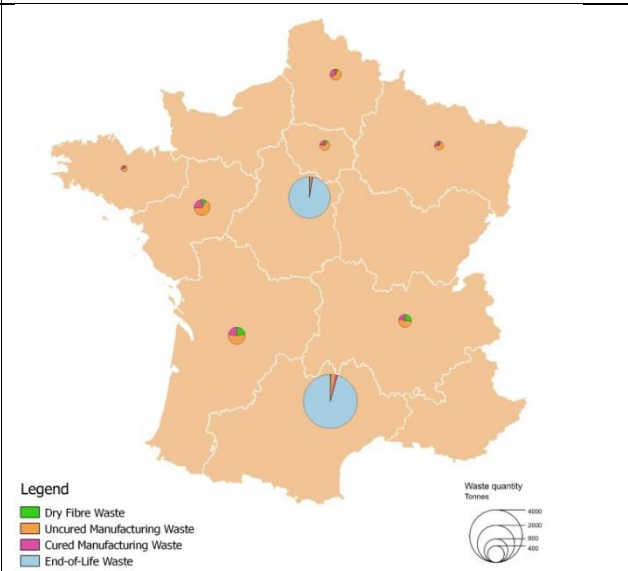
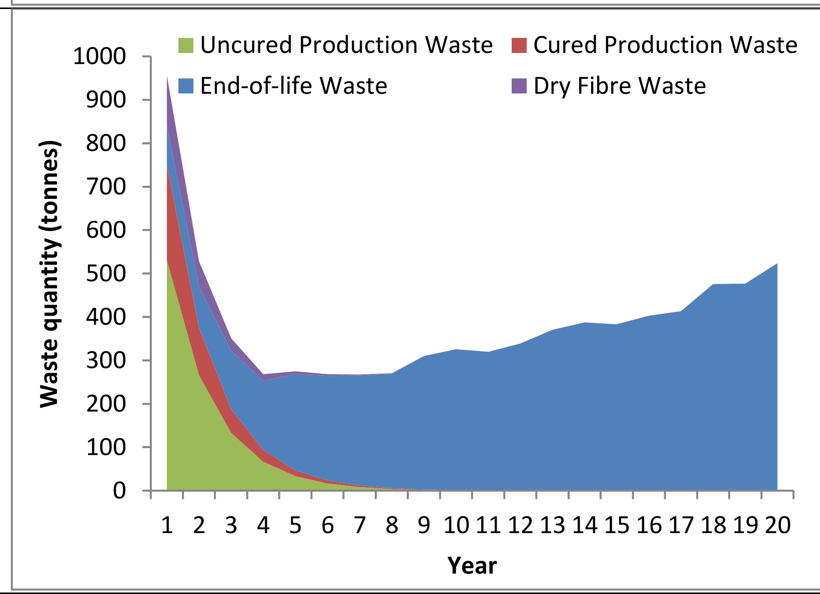
- For the *increasing trend*, the annual growth rate of Carbon Composites for Aerospace and Defence Sector is expected to be at 13 % (Witten et al., 2015), while the world passenger air-traffic will grow at around 5 % per year (4.6 % - (Airbus, 2015); 4.9 % - (Boeing, 2015)) for the 20-year period from 2015 to 2034. Production wastes are assumed to follow these evolutions and have the same annual growth rate in the horizon time of the study with 13 % for a strong increase 5 % for a light trend, respectively.

- For the *decreasing trend*, no public information is found about the policy of reduction of manufacturing wastes in Aerospace CFRP industry. Therefore, two scenarios have been considered considering an annual reduction rate of 50 % and 5 % for Strong Decrease and Light Decrease respectively. Indeed, the decreasing evolution needs a particular attention regarding the current situation for which recyclers may have difficulties to work at full capacity and may stop recycling operation due to the shortage of waste flows, or to waste reduction policy at the composites manufacturers as a consequence of process efficiency improvement. Based on these assumptions, the waste evolution takes place on the same region, no new waste source appears geographically during the horizon time of the study. The characteristics of the waste scenarios with their snapshot of waste quantity are summarised in Table 5-1.

Table 5-1: Snapshot of wastes distribution and annual evolution in waste scenarios

<table>
<tr><td>Scenarios</td><td>Map of Wastes</td><td>Evolution of total wastes from year 1 to year 20</td></tr>
<tr><td>Business as usual</td><td>
</td><td>
</td></tr>
</table>

<table>
<tr><td>Strong Increase</td><td>
</td><td>
</td></tr>
<tr><td>Light Increase</td><td>
</td><td>
</td></tr>
</table>

<table>
<tr>
<td>Light Decrease</td>
<td>
</td>
<td>
</td>
</tr>
<tr>
<td>Strong Decrease</td>
<td>
</td>
<td>
</td>
</tr>
</table>

5.2.2. Characteristics of waste treatment networks

Regarding the existing installation in the system, the recycling sites and the non-recovery pathways are kept the same as in the previous chapter. The non-recovery pathways including landfill, incineration and co-incineration are assumed to be available with a capacity of 3000 tonnes per year for all regions. The existing recovery plants are: grinding in Bretagne (BRE) (500 tonnes/year) and in Auvergne Rhône-Alpes (ARA) (3000 tonnes/year), pyrolysis in BRE (500 tonnes/year) and supercritical water in Pays-de-la-Loire (PL) (200 tonnes/year).

In this multi-period approach, new recycling sites can be created in order to extend the recovery capacity of the system regardless the period and region. The deployed recycling sites are activated at the beginning of a given year ***t*** and kept available until the end of the project only if the decision of investment is made in the precedent year (***t-1***). Therefore, year 0 is used for deployment decision that makes new recycling sites get ready for recovery of wastes at the beginning of the project, i.e. year 1. In function of its maturity, each technique can be provided with a range of three sizes (small-medium-large) corresponding to its scale for implementation of new plant (Table 5-2).

Table 5-2: Capacity of each scale for new deployed recycling site

$CAPR0_{rs}$ (tonnes/year)	Plant scale (***s***)		
	Small	Medium	Large
Grinding (Mechanical)	1000	2000	4000
Pyrolysis	500	1000	2000
Supercritical Water	200	500	1000
Microwave	500	1000	2000

5.2.3. Methodology

Through optimisation, each configuration consists in designing the creation of recycling sites (time and location of deployment, technique and scale), in allocating waste to different waste treatment techniques, and determining the average price of recovered fibre. To reach this goal, several bottlenecks are encountered and need to be overcome in the model. Indeed, the strategy must take into account: multiple waste types, multiple waste treatment options, different qualities for recovered products, dynamic variation of waste quantity, and diverse economic values of recovered fibres. Regarding the extension of the model compared with the one presented in the preceding chapter, a multi-step strategy is adopted for two bi-criteria optimisation approaches, i.e. cost-GWP minimisation and NPV maximisation-GWP minimisation in each scenario of waste evolution. For these two bi-criteria optimisation problems, a hybrid optimisation method combining lexicographic and ε-constraint method is used to build the Pareto front, following the same approach as in Chapter 4. M-TOPSIS method is then applied to select the compromise for the objectives among the optimal solutions of Pareto front.

As it is illustrated by Figure 5-1, several steps of this strategy are followed to optimise the whole system:

- Step 1: firstly, for each waste evolution scenario, the total cost (COST) and GWP impacts (GWP) are minimised in the system. This step allows determining the average prices of recycled fibres through the total cost.

- Step 2: then, a range of fixed prices for recycled fibres which are based on the values of prices calculated in Step 1, are used for the maximisation of the NPV of the system and for the minimisation of GWP impacts, simultaneously with application of M-TOPSIS.

- Step 3: another multi-criteria decision-making (MCDM) method, i.e. PROMETHEE, is adopted to consider the criterion of the price of recycled fibre, besides NPV and GWP among the set of optimal solutions obtained. Through the pairwise comparisons of the concordance and the discordance tests, PROMETHEE permits to determine relations between solutions/actions, and to avoid the underestimation of the similar effects on the studied criteria of some solutions which can be ignored in the classification based only on the ranking of distances between the given solutions and Nadir and Utopia points in M-TOPSIS method.

As the market of recycled carbon fibres is not yet established, it is necessary to have a price as low as possible to compete with other fibres. For a given waste evolution scenario, PROMETHEE method will rank all the so-called optimal solutions (the M-TOPSIS solution and the two mono-objective solutions at minimum GWP and maximum NPV of each price) regarding three objectives: minimisation of price, minimisation of GWP and maximisation of NPV. The best compromise solution will be rank at the first place after this step. Furthermore, the strategy on priority weights of each criterion in ranking is also considered and detailed in the results section.

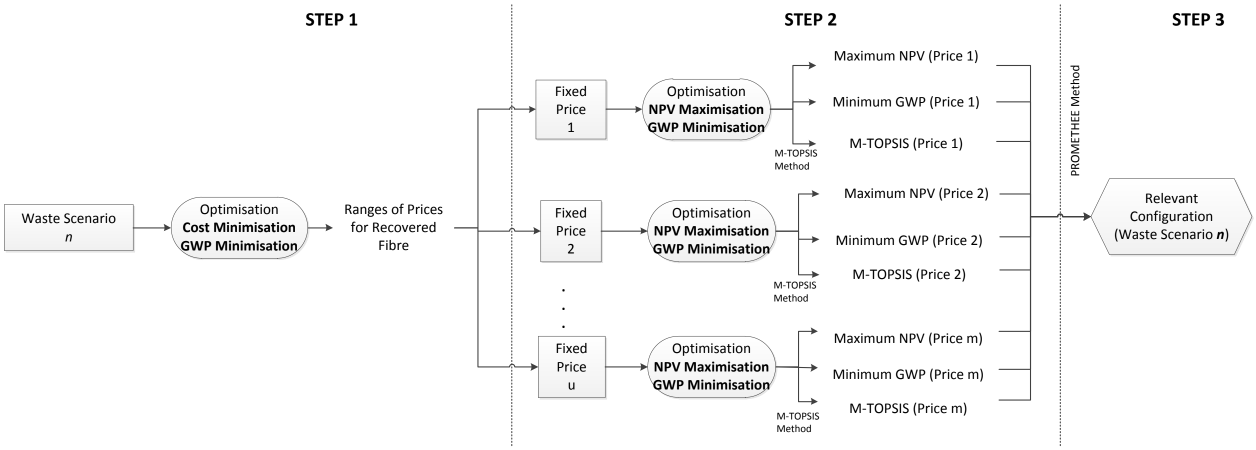


Figure 5-1: Procedure of optimisation process in each waste scenario

5.3. Problem formulation

The CFRP waste management system is modelled as a multi-period problem in order to take into account the annual variation of waste quantity. This dynamic consideration has been inserted in the model presented in Chapter 4:

- The time period has been discretised with a 1-year step.

- Besides the Non recovery techniques and the existing recycling sites, the system allows deployment of new recycling plants with different scales and techniques (Figure 5-2).

- In new recycling sites, waste storage is possible in order to avoid the shortage of waste input and the overflow for capacity. The cost of this activity is based on the quantity of stocked waste and the waste types, which will be presented in detail in the calculation of the objective function of COST with the equation (5.57).

The choices of scale, technique, time and location for deployment of new recycling sites are chosen through integer variables in the optimisation step. These modifications transform the initial problem into a mixed integer linear programming (MILP) model which is developed in GAMS environment and solved by CPLEX 12. Once the decision of investment has been made, the new sites are available during the next years for recycling wastes.

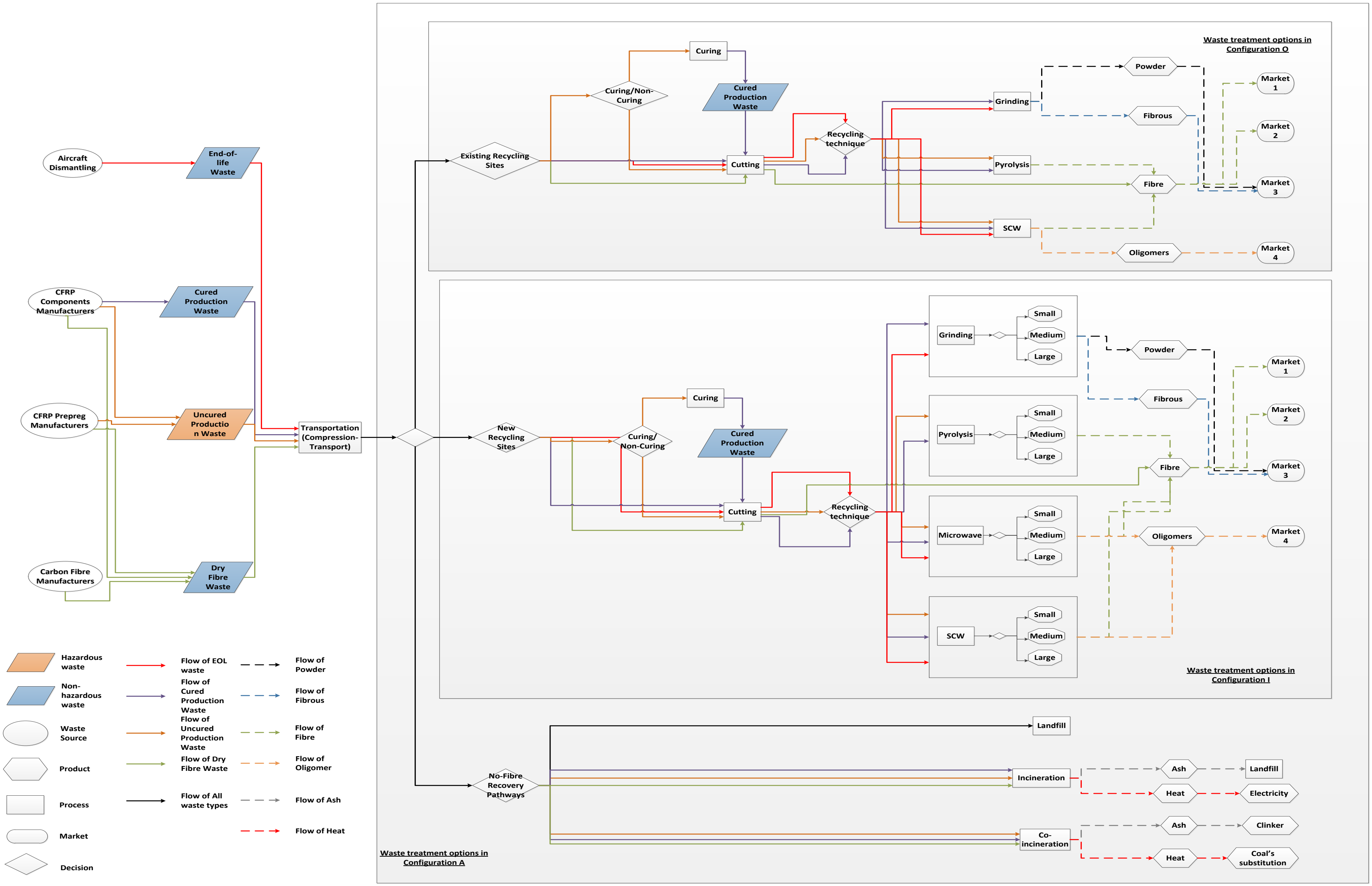


Figure 5-2: Input and Output of the modelled system

5.3.1. Constraints

5.3.1.1. Deployment of new recycling sites

The implementation or not of a new recycling site is expressed by a binary variable (***YRSTL**$_{rstl}$*) and depends on the recovery technique (***r***), the scale (***s***), the year of investment (***t***) and its location (***l***). Each new site can be created at different scales corresponding to different capacities of recycling (***CAPR0**$_{rs}$*). Equations (5.1) to (5.3) describe the formulation of recycling capacity of new recovery plants. Storage capacity in the new sites follows a linear relationship according to recycling capacity (5.4).

$$CAPRTU_{rstl} = CAPR0_{rs} \times YRSTL_{rsl}^{t-1}, \forall r \in \mathscr{R}, \forall s \in \mathscr{S}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \quad (5.1)$$

$$CAPRTU_{rsl}^{t=0} = 0, \forall r \in \mathscr{R}, \forall s \in \mathscr{S}, \forall l \in \mathscr{L} \quad (5.2)$$

$$CAPRT_{rstl} = \sum_{t'=0}^{t} CAPRTU_{rst'l}, \forall r \in \mathscr{R}, \forall s \in \mathscr{S}, \forall t, t' \in \mathscr{T}, \forall l \in \mathscr{L} \quad (5.3)$$

$$CAPST_{rstl} = CAPRT_{rstl} \times \omega, \forall r \in \mathscr{R}, \forall s \in \mathscr{S}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \quad (5.4)$$

5.3.1.2. Waste quantity conservation

All the wastes generated at source ***l*** have to be treated completely through either Non recovery (***FWNR**$_{wetl}$*) or Fibre Recovery pathways. In the Fibre Recovery pathways, wastes can go to the existing sites (***FWRO**$_{wrtll'}$*) or to the new sites (***FWRI**$_{wrtll'}$*). Each output flow of each waste type ***w*** at source ***l*** at time ***t*** has to be equal to the waste quantity of that waste type at the same location and period (5.5).

$$\sum_{e \in \mathscr{E}} FWNR_{wetl} + \sum_{r \in \mathscr{R}} \sum_{l' \in \mathscr{L}} FWRO_{wrtll'} + \sum_{r \in \mathscr{R}} \sum_{l' \in \mathscr{L}} FWRI_{wrtll'} = QW_{wtl}, \forall w \in \mathscr{W}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \quad (5.5)$$

The waste flows into Non recovery techniques are treated on site because they are considered available at all regions and there is no transportation of these streams according to the results found in the previous chapter. The recycling process is the same as already presented with two options:

- Pretreatment step and recycling process are separated for ***FWROPR**$_{wrtl}$* (existing sites) and ***FWRIPR**$_{wrtl}$* (new sites);
- Direct recycling in which pretreatement can be integrated in function of the adaptability of process ***r*** with waste ***w*** for ***FWRODR**$_{wrtl}$* (existing sites) and ***FWRIDR**$_{wrtl}$* (new sites).

Equation (5.6) expresses the mass balance of waste flows in the existing sites. In the deployed sites, wastes can be pre-treated, directly recycled or stored (Eq. (5.7) and (5.8)).

$$FWROPR_{wrtl'} + FWRODR_{wrtl'} = \sum_{l \in \mathscr{L}} FWRO_{wrtll'}, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l' \in \mathscr{L} \tag{5.6}$$

$$QWRS^{t+1}_{wrl'} = QWRS^{t}_{wrtl'} + \sum_{l \in \mathscr{L}} FWRI^{t+1}_{wrll'} - FWRIPR^{t+1}_{wrl'} - FWRIDR^{t+1}_{wrl'}, \\ \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l' \in \mathscr{L} \tag{5.7}$$

$$\sum_{l \in \mathscr{L}} FWRI^{t=0}_{wrll'} = FWRIPR^{t=0}_{wrl'} + FWRIDR^{t=0}_{wrl'} + QWRS^{t=0}_{wrl'}, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall l' \in \mathscr{L} \tag{5.8}$$

5.3.1.3. Capacity constraints

The inputs of all waste types are taken into account in waste treatment capacity of each plant. Therefore, the total waste streams which go into Non recovery techniques are constrained by a maximal value determined by the capacity of these techniques (5.9). The flow of waste, which is pre-treated separately, is lower than the capacity of pre-treatment which is equal to the total of capacity of all recycling techniques at the same location (5.10) and (5.12). All input streams of each recycling plant are inferior to its capacity (5.11) and (5.13). The total quantity of stored wastes has to be under the storage capacity for each deployed site (5.14).

$$\sum_{w \in \mathscr{W}} FWNR_{wetl} \le CAPEL_{el}, \forall e \in \mathscr{E}, \forall l' \in \mathscr{L} \tag{5.9}$$

$$\sum_{w \in \mathscr{W}} \sum_{r \in \mathscr{R}} FWROPR_{wrtl} \le \sum_{r \in \mathscr{R}} CAPROL_{rl}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.10}$$

$$\sum_{w \in \mathscr{W}} FWRODR_{wrtl'} + \sum_{i \in \mathscr{I}} \sum_{l \in \mathscr{L}} FIOR_{irtll'} \le CAPROL_{rl'}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l' \in \mathscr{L} \tag{5.11}$$

$$\sum_{w \in \mathscr{W}} \sum_{r \in \mathscr{R}} FWRIPR_{wrtl} \le \sum_{r \in \mathscr{R}} \sum_{s \in \mathscr{S}} CAPRT_{rstl}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.12}$$

$$\sum_{w \in \mathscr{W}} FWRIDR_{wrtl'} + \sum_{i \in \mathscr{I}} \sum_{l \in \mathscr{L}} FIIR_{irtll'} \le \sum_{s \in \mathscr{S}} CAPRT_{rstl'}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l' \in \mathscr{L} \tag{5.13}$$

$$\sum_{w \in \mathscr{W}} QWRS_{wrtl} \le \sum_{s \in \mathscr{S}} CAPST_{rstl}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.14}$$

5.3.1.4. Non negativity constraints

All streams of wastes, intermediate products and recovered final products cannot take negative values according to the set of constraints from (5.15) to (5.28).

$$FWNR_{wetl} \geq 0, \forall w \in \mathscr{W}, \forall e \in \mathscr{E}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.15}$$

$$FWROPR_{wrtl} \geq 0, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.16}$$

$$FWRODR_{wrtl} \geq 0, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.17}$$

$$FIOR_{irtll'} \geq 0, \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.18}$$

$$FWRIPR_{wrtl} \geq 0, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.19}$$

$$FWRIDR_{wrtl} \geq 0, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.20}$$

$$FIIR_{irtll'} \geq 0, \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.21}$$

$$QWRS_{wrtl} \geq 0, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.22}$$

$$FPOPR_{wrpctll'} \geq 0, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.23}$$

$$FPODR_{wrpctll'} \geq 0, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.24}$$

$$FPOIR_{irpctll'} \geq 0, \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.25}$$

$$FPIPR_{wrpctll'} \geq 0, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.26}$$

$$FPIDR_{wrpctll'} \geq 0, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.27}$$

$$FPIIR_{irpctll'} \geq 0, \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.28}$$

5.3.1.5. Acceptability constraints

Similarly to the approach in Chapter 4, the wastes can be accepted in a waste treatment pathway depending on their relevance to the treatment technique and waste type in this chapter. Therefore, according to the acceptability index which is a binary parameter to accept (with value 1) or not (with value 0) waste to technique, the waste streams to each treatment route are restricted by the constraints (5.29) to (5.31) and (5.39) to (5.40). Similarly, the adaptability of intermediate products after pre-treatment step in recycling technique is under the constraints (5.32) and (5.41).

The constraints (5.33) to (5.35) and (5.42) to (5.44) show the acceptability of recovered product streams to the corresponding market. Besides the types of recovered products, each market requires a minimum quality of products so that they can be accepted to that market (see Appendix 4). These constraints are shown by (5.36) to (5.38) and (5.45) to (5.47).

<u>Flows of wastes in the Non-Recovery paths:</u>

$$FWNR_{wetl} \leq XWNR_{we} \times QW_{wtl}, \forall w \in \mathscr{W}, \forall e \in \mathscr{E}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.29}$$

<u>Flows of wastes/recovered products in the existing recovery sites:</u>

Constraints of recycling techniques and waste types:

$$FWRODR_{wrtl} \leq M \times XWR_{wr}, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.30}$$

$$FWROPR_{wrtl} \leq M \times XWPR_w, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l \in \mathscr{G} \tag{5.31}$$

$$\sum_{l' \in \mathscr{L}} FIOR_{irtll'} \leq QIOR_{itl} \times XIR_{ir}, \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l \in \mathscr{G}$$

with $$QIOR_{itl} = \sum_{\substack{r \in \mathscr{R} \\ w \in \mathscr{W}}} \left[FWROPR_{wrtl} \times (1 - XPR_w) \right] \times XWI_{wi}, \forall i \in \mathscr{I}, \forall t \in \mathscr{T}, \forall l \in \mathscr{G} \tag{5.32}$$

Constraints of market locations for the distribution of recovered products:

$$\sum_{w \in \mathscr{W}} \sum_{r \in \mathscr{R}} \sum_{l \in \mathscr{L}} FPOPR_{wrpctll'} \leq M \times XDP_{cpl'}, \forall c \in \mathscr{C}, \forall p \in \mathscr{P}, \forall t \in \mathscr{T}, \forall l' \in \mathscr{G}$$

with $$\sum_{c \in \mathscr{C}} \sum_{l' \in \mathscr{L}} FPOPR_{wrpctll'} = FWROPR_{wrtl} \times XPR_w \times XPRP_{wp}, \quad \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.33}$$

$$\sum_{w \in \mathscr{W}} \sum_{r \in \mathscr{R}} \sum_{l \in \mathscr{L}} FPODR_{wrpctll'} \leq M \times XDP_{cpl'}, \forall c \in \mathscr{C}, \forall p \in \mathscr{P}, \forall t \in \mathscr{T}, \forall l' \in \mathscr{G}$$

with $$\sum_{c \in \mathscr{C}} \sum_{l' \in \mathscr{L}} FPODR_{wrpctll'} = FWRODR_{wrtl} \times RWRP_{rpw} / 100, \quad \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.34}$$

$$\sum_{i \in \mathscr{I}} \sum_{r \in \mathscr{R}} \sum_{l \in \mathscr{L}} FPOIR_{irpctll'} \leq M \times XDP_{cpl'}, \forall c \in \mathscr{C}, \forall p \in \mathscr{P}, \forall t \in \mathscr{T}, \forall l' \in \mathscr{G}$$

with $$\sum_{c \in \mathscr{C}} \sum_{l' \in \mathscr{L}} FPOIR_{irpctll'} = \sum_{l'' \in \mathscr{L}} FIOR_{irtl''l} \times RIRP_{rpi} / 100, \quad \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.35}$$

Constraints of minimum quality for acceptability in each market for recovered products from recycling techniques:

$$FPODR_{wrpctll'} \times QLRPW_{wrp} \geq FPODR_{wrpctll'} \times CQL_{cp} \quad \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.36}$$

$$FPOIR_{irpctll'} \times QLRPI_{irp} \geq FPOIR_{irpctll'} \times CQL_{cp} \quad \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.37}$$

$$FPOPR_{wrpctll'} \times QLPRP_{wp} \geq FPOPR_{wrpctll'} \times CQL_{cp} \quad \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.38}$$

Flows of wastes/recovered products in the deployed recovery sites:

Constraints of recycling techniques and waste types:

$$FWRIDR_{wrtl} \leq M \times XWR_{wr}, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.39}$$

$$FWRIPR_{wrtl} \leq M \times XWPR_{w}, \forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L} \tag{5.40}$$

$$\sum_{l' \in \mathscr{L}} FIIR_{irtll'} \leq QIIR_{itl} \times XIR_{ir}, \forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L}$$

with $QIIR_{itl} = \sum_{w \in \mathscr{W}} \sum_{r \in \mathscr{R}} \left[FWRIPR_{wrtl} \times (1 - XPR_{w}) \right] \times XWI_{wi}, \forall i \in \mathscr{I}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L}$ (5.41)

Constraints of market locations for the distribution of recovered products:

$$\sum_{w \in \mathscr{W}} \sum_{r \in \mathscr{R}} \sum_{l \in \mathscr{L}} FPIPR_{wrpctll'} \leq M \times XDP_{cpl'}, \forall c \in \mathscr{C}, \forall p \in \mathscr{P}, \forall t \in \mathscr{T}, \forall l' \in \mathscr{L}$$

with $\sum_{c \in \mathscr{C}} \sum_{l' \in \mathscr{L}} FPIPR_{wrpctll'} = FWRIPR_{wrtl} \times XPR_{w} \times XPRP_{wp},$
$\forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L}$ (5.42)

$$\sum_{w \in \mathscr{W}} \sum_{r \in \mathscr{R}} \sum_{l \in \mathscr{L}} FPIDR_{wrpctll'} \leq M \times XDP_{cpl'}, \forall c \in \mathscr{C}, \forall p \in \mathscr{P}, \forall t \in \mathscr{T}, \forall l' \in \mathscr{L}$$

with $\sum_{c \in \mathscr{C}} \sum_{l' \in \mathscr{L}} FPIDR_{wrpctll'} = FWRIDR_{wrtl} \times RWRP_{rpw} / 100,$
$\forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L}$ (5.43)

$$\sum_{i \in \mathscr{I}} \sum_{r \in \mathscr{R}} \sum_{l \in \mathscr{L}} FPIIR_{irpctll'} \leq M \times XDP_{cpl'}, \forall c \in \mathscr{C}, \forall p \in \mathscr{P}, \forall t \in \mathscr{T}, \forall l' \in \mathscr{L}$$

with $\sum_{c \in \mathscr{C}} \sum_{l' \in \mathscr{L}} FPIIR_{irpctll'} = \sum_{l'' \in \mathscr{L}} FIIR_{irtl''l} \times RIRP_{rpi} / 100,$
$\forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall t \in \mathscr{T}, \forall l \in \mathscr{L}$ (5.44)

Constraints of minimum quality for acceptability in each market for recovered products from recycling techniques:

$$FPIDR_{wrpctll'} \times QLRPW_{wrp} \geq FPIDR_{wrpctll'} \times CQL_{cp}$$
$$\forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.45}$$

$$FPIIR_{irpctll'} \times QLRPI_{irp} \geq FPIIR_{irpctll'} \times CQL_{cp}$$
$$\forall i \in \mathscr{I}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.46}$$

$$FPIPR_{wrpctll'} \times QLPRP_{wp} \geq FPIPR_{wrpctll'} \times CQL_{cp},$$
$$\forall w \in \mathscr{W}, \forall r \in \mathscr{R}, \forall p \in \mathscr{P}, \forall c \in \mathscr{C}, \forall t \in \mathscr{T}, \forall l, l' \in \mathscr{L} \tag{5.47}$$

5.3.2. Objective functions

5.3.2.1. Minimisation of total cost (COST)

The total cost of the system (***COST***) depends on the investment cost for new recycling sites and on all the costs of the system activities (5.48). In each period, the investment cost (***CINVT$_t$***) is calculated by Eq. (5.49). Besides the costs of transportation, operation and distribution of recovered products, labour and maintenance costs of deployed sites are included in the cost of activities per year (***CACT$_t$***). Its components are presented in detail in equations (5.50) to (5.57).

$$COST = \sum_{t \in \mathscr{T}} CINVT_t + \sum_{t \in \mathscr{T}} CACT_t \tag{5.48}$$

$$CINVT_t = \sum_{r \in \mathscr{R}} \sum_{s \in \mathscr{S}} \sum_{l \in \mathscr{L}} \left(INV0_{rs} \times YRSTL_{rstl} \right), \forall t \in \mathscr{T} \tag{5.49}$$

$$CACT_t =$$

$$+\left[\sum_{r \in \mathscr{R}} \sum_{s \in \mathscr{S}} \sum_{l \in \mathscr{L}} \left(OCOST_{rs} \times YRSTLT_{rstl} \right) \right] + \tag{5.50}$$

(Other costs (labour, maintenance…))

$$YRSTLT_{rstl} = \sum_{t'=0}^{t-1} YRSTL_{rst'l}$$

$$YRSTLT_{rsl}^{t=0} = 0$$

with $\forall r \in \mathscr{R}, \forall s \in \mathscr{S}, \forall l \in \mathscr{L}, \forall t, t' \in \mathscr{G}$

$$+\left[\sum_{w \in \mathscr{W}} \sum_{e \in \mathscr{E}} \sum_{l \in \mathscr{L}} \left(FWNR_{wetl} \times PNR_{ew} \right) \right] + \tag{5.51}$$

(Cost of Non recovery pathways)

$$+\left\{ \sum_{w \in \mathscr{W}} \sum_{i \in \mathscr{I}} \sum_{r \in \mathscr{R}} \sum_{l,l' \in \mathscr{L}} \begin{bmatrix} \left(FWRO_{wrtll'} + FWRI_{wrtll'} \right) \times PTR_w + \\ + \left(FIOR_{irtll'} + FIIR_{irtll'} \right) \times PTR0 \end{bmatrix} \times DIST_{ll'} \right\} + \tag{5.52}$$

(Transport cost)

$$+\left\{ \sum_{w \in \mathscr{W}} \sum_{i \in \mathscr{I}} \sum_{r \in \mathscr{R}} \sum_{l,l' \in \mathscr{L}} \left[\left(FWRO_{wrtll'} + FWRI_{wrtll'} + FIOR_{irtll'} + FIIR_{irtll'} \right) \times XTR_{ll'} \times PCOM \right] \right\} + \tag{5.53}$$

(Compression cost)

$$+\left\{ \sum_{w \in \mathscr{W}} \sum_{r \in \mathscr{R}} \sum_{l \in \mathscr{L}} \left[\left(FWROPR_{wrtl} + FWRIPR_{wrtl} \right) \times EPR_w \times PE \right] \right\} + \tag{5.54}$$

(Pretreatment cost)

$$+\left\{ \sum_{r \in \mathscr{R}} \sum_{l \in \mathscr{L}} \begin{bmatrix} \sum_{w \in \mathscr{W}} \left[\left(FWRODR_{wrtl} + FWRIDR_{wrtl} \right) \times PWR_{rw} \right] \\ + \sum_{i \in \mathscr{I}} \left[\left(FIOR_{irtll'} + FIIR_{irtll'} \right) \times PIR_{ri} \right] \end{bmatrix} \right\} + \tag{5.55}$$

(Cost of recycling process)

$$+\left\{\sum_{l,l'\in\mathscr{L}}\left[\left[\sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{c\in\mathscr{C}}\sum_{p\in\mathscr{P}}\sum_{r\in\mathscr{R}}\begin{pmatrix}FPOPR_{wrpctll'}+FPODR_{wrpctll'}+\\+FPOIR_{irpctll'}+FPIPR_{wrpctll'}+\\+FPIDR_{wrpctll'}+FPIIR_{irpctll'}\end{pmatrix}\right]\times DIST_{ll'}\times PTR0\right]\right\}+ \quad (5.56)$$

(Cost of distribution of recovered product)

$$+\left[\sum_{w\in\mathscr{W}}\sum_{r\in\mathscr{R}}\sum_{l\in\mathscr{L}}\left(QWRS_{wrtl}\times PSTW_{w}\right)\right] \quad (5.57)$$

(Cost of storage)

5.3.2.2. Maximisation of Net Present Value

The Net Present Value is maximised at the end of the project, i.e. the end of the 20th year (***NPV***) (5.58). The value of Net Present Value in each year in the horizon time (***NPVTS$_t$***) is calculated according to Eq. (5.59) including a tax rate (***α***) and a discount rate (***β***). In this formula, the revenue before tax (***RBTS$_t$***) is expressed by (5.60). In function of the profitability at each year, the revenue can be taxed (5.59a) or not (5.59b), i.e. if recycling activities generate revenue (positive profit), they have to pay tax; if they have no revenue or are debited, no tax are imposed. To simplify mathematical programming into MILP, the formula (5.59a) is applied to calculate in modelling ***NPVTS$_t$*** whatever the positivity of RBTS for optimisation. In the year when RBTS is negative, ***NPVTS$_t$*** and ***NPV*** are recalculated manually by the formula (5.59b) to represent in Pareto front. As the imposed lifespan of a new recycling site is 10 years, the depreciation cost (***DEP$_t$***) is calculated by (5.61). The profits from recovered products (***REVT$_t$***) are presented in detail in Eqs. (5.62) to (5.65).

$$NPV = NPVTS_{t=20} \quad (5.58)$$

$$NPVTS_{t}=\sum_{t'=0}^{t}\frac{RBTS_{t'}\times(1-\alpha)+DEP_{t'}-CINVT_{t'}}{(1+\beta)^{t'}},\forall t\in\mathscr{T},\text{if } RBTS_{t'}\geq 0 \quad (5.59a)$$

$$NPVTS_{t}=\sum_{t'=0}^{t}\frac{RBTS_{t'}+DEP_{t'}-CINVT_{t'}}{(1+\beta)^{t'}},\forall t\in\mathscr{T},\text{if } RBTS_{t'}< 0 \quad (5.59b)$$

$$RBTS_{t}=REVT_{t}-CACT_{t}-DEP_{t} \quad (5.60)$$

$$DEP_{t=0}=0$$
$$DEP_{1\leq t\leq 10}=\sum_{t'=0}^{t-1}\frac{CINVT_{t'}}{10} \quad (5.61)$$
$$DEP_{11\leq t\leq 20}=\sum_{t'=0}^{t-1}\frac{CINVT_{t'}}{10}-\sum_{t'=0}^{t-11}\frac{CINVT_{t'}}{10}$$

$$REVT_t =$$

$$\left\{\sum_{w\in\mathscr{W}}\sum_{r\in\mathscr{R}}\sum_{p\in\mathscr{P}}\sum_{c\in\mathscr{C}}\sum_{l,l'\in\mathscr{L}}\left[\left(FPODR_{wrpctll'}+FPIDR_{wrpctll'}\right)\times PP_p\times QLRPW_{wrp}/100\right]\right\}+ \tag{5.62}$$

(revenue from recovered products from directed recycling)

$$+\left\{\sum_{i\in\mathscr{I}}\sum_{r\in\mathscr{R}}\sum_{p\in\mathscr{P}}\sum_{c\in\mathscr{C}}\sum_{l,l'\in\mathscr{L}}\left[\left(FPOIR_{irpctll'}+FPIIDR_{irpctll'}\right)\times PP_p\times QLRPI_{irp}/100\right]\right\}+ \tag{5.63}$$

(revenue from recovered products through intermediate step

$$+\left\{\sum_{w\in\mathscr{W}}\sum_{r\in\mathscr{R}}\sum_{p\in\mathscr{P}}\sum_{c\in\mathscr{C}}\sum_{l,l'\in\mathscr{L}}\left[\left(FPOPR_{wrpctll'}+FPIPR_{wrpctll'}\right)\times PP_p\times QLRPP_{wp}/100\right]\right\}+ \tag{5.64}$$

(revenue from recovered products from pretreatment step

$$+\left[\sum_{w\in\mathscr{W}}\sum_{e\in\mathscr{E}}\sum_{l\in\mathscr{L}}\left(FWNR_{wetl}\times RNR_e\right)\right] \tag{5.65}$$

(revenue from non recovery pathways

5.3.2.3. Minimisation of the GWP impacts (GWP)

The unit GWP impacts are evaluated from Simapro v7.3 with ReCiPe Midpoint (H) v.1.06 assessment method and collected from literature (see Chapter 3, Section 3.2.3 for the numerical values). The GWP impact of the system in this model is expressed as follows:

GWP =

$$\left[\sum_{w\in\mathscr{W}}\sum_{e\in\mathscr{E}}\sum_{t\in\mathscr{T}}\sum_{l\in\mathscr{L}}\left(FWNR_{wetl}\times GWPNRU_e\right)\right]+ \tag{5.66}$$

(Non recovery activities impacts)

$$+\left\{\sum_{l,l'\in\mathscr{L}}\left[\left[\sum_{i\in\mathscr{I}}\sum_{w\in\mathscr{W}}\sum_{r\in\mathscr{R}}\sum_{t\in\mathscr{T}}\begin{pmatrix}FWRO_{wrtll'}+FWRI_{wrtll'}+\\+FIOR_{irtll'}+FIIR_{irtll'}\end{pmatrix}\right]\times DIST_{ll'}\times GWPTRU\right]\right\}+ \tag{5.67}$$

(Transport impacts)

$$+\left\{\sum_{l,l'\in\mathscr{L}}\left[\left[\sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{r\in\mathscr{R}}\sum_{t\in\mathscr{T}}\begin{pmatrix}FWRO_{wrtll'}+FWRI_{wrtll'}+\\+FIOR_{irtll'}+FIIR_{irtll'}\end{pmatrix}\right]\times XTR_{ll'}\times ECOM\times 3.6\times GWPE\right]\right\}+ \tag{5.68}$$

(Compression impacts)

$$+\left\{\sum_{w\in\mathscr{W}}\sum_{r\in\mathscr{R}}\sum_{t\in\mathscr{T}}\sum_{l\in\mathscr{L}}\left[\left(FWROPR_{wrtl}+FWRIPR_{wrtl}\right)\times EPR_w\times 3.6\times GWPE\right]\right\}+ \tag{5.69}$$

(Pretreatment activity impacts)

$$+\left\{\begin{array}{l}\sum_{w\in\mathscr{W}}\sum_{r\in\mathscr{R}}\sum_{t\in\mathscr{T}}\sum_{l\in\mathscr{L}}\left[\left(FWRODR_{wrtl}+FWRIDR_{wrtl}\right)\times GWPWR_{rw}\right]+\\+\sum_{i\in\mathscr{I}}\sum_{r\in\mathscr{R}}\sum_{t\in\mathscr{T}}\sum_{l,l'\in\mathscr{L}}\left[\left(FIOR_{irtll'}+FIIR_{irtll'}\right)\times GWPIR_{ri}\right]\end{array}\right\}+ \tag{5.70}$$

(Recycling activity impacts)

$$+\left\{\sum_{l,l'\in\mathscr{L}}\left[\left[\sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{r\in\mathscr{R}}\sum_{p\in\mathscr{P}}\sum_{c\in\mathscr{C}}\sum_{t\in\mathscr{T}}\begin{pmatrix}FPOPR_{wrpctll'}+FPODR_{wrpctll'}+\\+FPOIR_{irpctll'}+FPIPR_{wrpctll'}+\\+FPIDR_{wrpctll'}+FPIIR_{irpctll'}\end{pmatrix}\right]\times DIST_{ll'}\times GWPTRU\right]\right\}+ \tag{5.71}$$

(Distribution impacts)

$$-\left\{\begin{array}{l}\sum_{w\in\mathscr{W}}\sum_{e\in\mathscr{E}}\sum_{t\in\mathscr{T}}\sum_{l\in\mathscr{L}}\left(FWNR_{wetl}\times GWPNRAU_{we}\right)+\\+\sum_{w\in\mathscr{W}}\sum_{i\in\mathscr{I}}\sum_{r\in\mathscr{R}}\sum_{p\in\mathscr{P}}\sum_{c\in\mathscr{C}}\sum_{t\in\mathscr{T}}\sum_{l,l'\in\mathscr{L}}\left[\begin{pmatrix}FPOPR_{wrpctll'}+FPODR_{wrpctll'}+\\+FPOIR_{irpctll'}+FPIPR_{wrpctll'}+\\+FPIDR_{wrpctll'}+FPIIR_{irpctll'}\end{pmatrix}\times GWPP_{p}\right]\end{array}\right\} \tag{5.72}$$

(Avoided impacts from recovered products of Non recovery and Fibre recovery pathways)

5.4. Results and Discussions

5.4.1. Preliminary assessment of the existing recycling capacity

Before analysing the results of optimization, the current existing recycling capacities have to be compared with the evolution scenarios of wastes. Indeed, without the deployment of any new plant, the current system can recycle 3500 tonnes with grinding in BRE and ARA, 500 tonnes with pyrolysis in BRE and 200 tonnes with supercritical water in PL per year (see Chapter 4). Figure 5-3 shows the amount of wastes generated per year of the abovementioned scenarios compared to the current existing recycling capacities.

Without the presence of other composite wastes such as GFRP treated in the existing plants, all the wastes of the system during the horizon time can be treated completely by grinding for scenarios: BAU, Light Increase and both of Decrease Trend. However, in the scenario of Strong Increase, the high annual growth rate (δ=13%) raise the production wastes so rapidly that grinding cannot cover all wastes produced from the year 13. Even with the combination of other existing recovery techniques, all wastes in Strong Increase scenario cannot be treated completely, so that the implementation of new recycling plants is needed.

Table 5-1 has also presented the contribution of the different waste types in the scenarios. The number of dismantled aircraft per year has not been varied in the model, only the variation of CFRP rate in retired aircraft has been considered to act on the evolution of end-of-life waste during the horizon time: the end-of-life waste increases nearly 6 times from the beginning to the end of the project (year 20), however, compared to the current aircraft dismantling capacity, this waste does not exhibit a significant contribution among the production wastes (dry fibre, uncured and cured wastes) in Increase Trends, only 8.1 % of total waste in Strong Increase scenario for example.

Due to the higher treatment cost and small quantity in total streams, this waste may be completely treated by grinding which is the cheapest recycling route so that the available capacity of more advanced techniques is dedicated to more important waste streams. This waste becomes important from year 11 and year 3 in Light Decrease and Strong Decrease respectively. The recovery of end-of-life waste requires a global approach of aircraft manufacturers, airliners and dismantlers in order to avoid an underestimation of its available quantity and potential recovered value.

Let us recall that dry fibre waste is recycled by a pretreatment step for recovery and thus, does not affect the capacity of recycling process; the other wastes can be recycled by all existing techniques except end-of-life waste that cannot be treated by pyrolysis. Like grinding, SCW plant can treat all waste types but its low current capacity does not allow recycling all the wastes generated annually. With a small capacity, pyrolysis can be used to substitute grinding and SCW in recycling production wastes. To conclude, the deployment of new recycling plants under the pressure of waste flows is essential when the production wastes increase as in Strong Increase scenario.

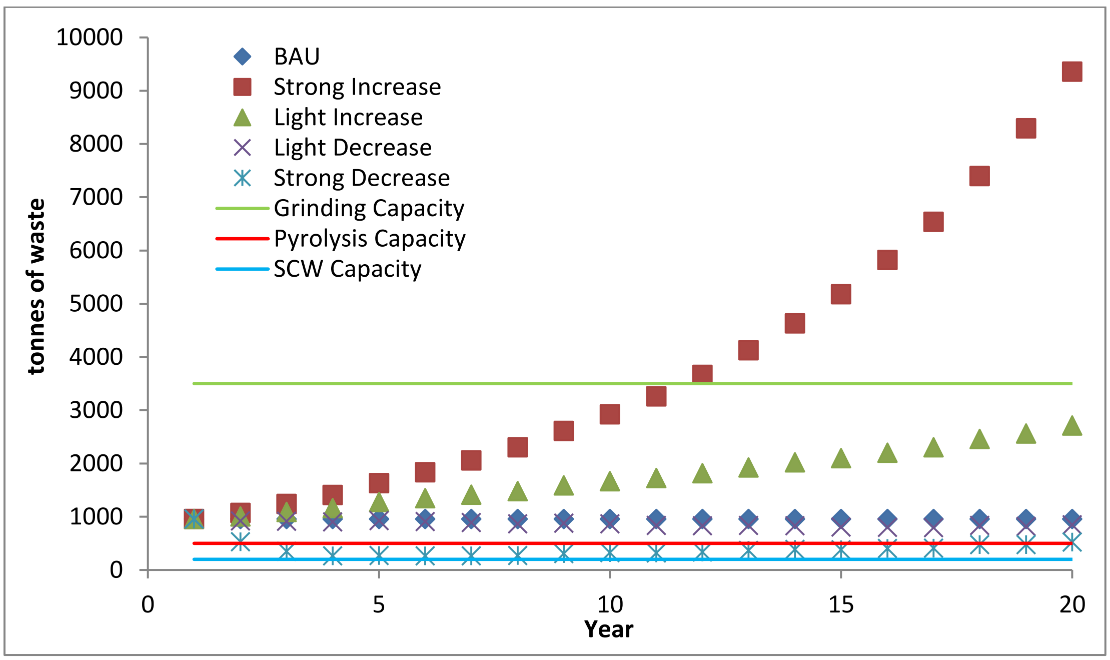


Figure 5-3: Quantity of wastes generated per year and recycling capacity of the existing plants from year 1 to year 20 in the studied waste scenarios

5.4.2. Cost-GWP Optimisation

5.4.2.1. Characteristics of Optimisation

The first step consists in a bi-criteria optimisation as Chapter 4, i.e. minimisation of total cost (COST) and minimisation of GWP impacts in the system. The ε-constraint method is applied to build the Pareto front which is constructed by minimising COST for successive intervals of GWP. In this step, only the first ten years of the horizon time (year 1 to year 10) are considered in order to test the flexibility of the system in different configurations and to reduce the computational time. A ten-year period also corresponds to the lifespan of a new deployed recycling plant. The decision of deployment is taken at year 0, so that the deployed site can be available from the year 1.

As highlighted in the preceding section, for the example considered, it is not necessary to build a new recovery site in the first ten years with the capacity of all Non recovery techniques and existing recycling sites. In this context, the waste management can be organised following three configurations based on policy of waste owners or government for responsibility of treatment of wastes generated in the system (Figure 5-2).

- In the first configuration (O for Outsourcing), the imposed strategy is full recovery with the existing sites, and the responsibility of waste treatment is transferred from waste producers to the third service, i.e. the existing recycling plants. The waste producers/owners may pay only recycling and do not need to invest. However, they cannot receive any economic benefit from recovered products which will be obtained by the recyclers. The wastes may be mixed with the other streams of the plants if there is no requirement for waste traceability in the recycling plants.

- In the second configuration (I for Internal Service), involves waste producers/owners set up an independent recovery system for all their wastes. The investment is needed to establish a recovery system. The waste streams can be easily controlled and tracked. If recovered products can be reused in the production process of the wastes producers, this structure is a closed-loop recycling system.

- Thirdly, an open system in which all waste treatment options are available is studied in the last structure (A for All options). Without the limitation of technique and boundary, this open configuration can help government/administration, which has arbitrary role optimise the recycling system.

For each configuration, the bi-criteria optimisation of COST and GWP minimisation is carried out in order to compare these three options. A Pareto front is built with the ε-constraint method.

Particularly, in the configuration I, a dominant solution can be observed in BAU (Figure 5-4), Light Increase, Light Decrease and Strong Decrease scenarios (not found in Strong Increase scenario), and the solutions dominated by this point are removed from Pareto front.

- Figure 5-4 shows an example of Pareto front of the configuration I in BAU scenario. In this Pareto front, three important solutions are determined: GWPmin corresponding to the mono-criteria solution that minimises GWP impacts, COSTmin for the minimum of the total cost and the optimal solution after M-TOPSIS analysis (M-TOPSIS). This latter corresponds also to the dominant solution in the configuration I of BAU, Light Increase, Light Decrease and Strong Decrease scenarios.

- This situation appears only in the configuration I because the optimisation problem includes too many constraints mainly due to the fixed capacity of each recycling technique and due to the non-linear relationship of investment cost between these techniques which have different TRL. It must be emphasized that the intervals chosen for the ε-constraint method have been chosen as large enough to search for a global optimum and to reduce the computational time. During the minimisation of COST for successive intervals of GWP, the GWP value of dominant solution is very close to GWPmin, around 98.8 to 99.3% of GWPmin (Table 5-3).

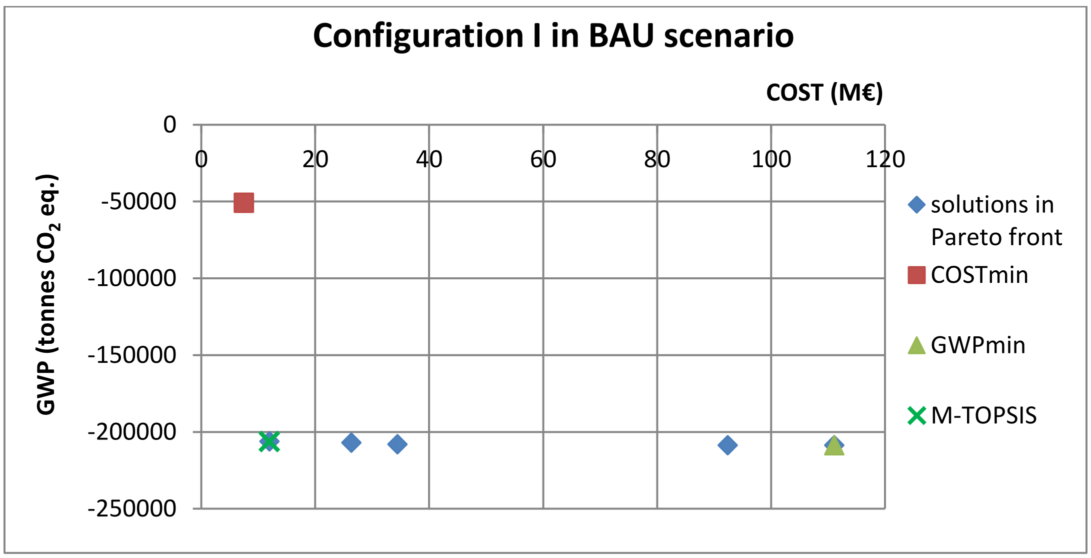


Figure 5-4: Pareto front of COST and GWP criteria for the configuration I in BAU scenario

Table 5-3: The ratio GWP/GWPmin at the dominant point observed in the configuration I of BAU, Light Increase, Light Decrease, and Strong Decrease scenarios

Waste Scenario	GWP/GWP_{min} (%)
BAU	98.84
Light Increase	98.90
Light Decrease	98.96
Strong Decrease	99.31

5.4.2.2. Three configurations in the studied waste management

The Pareto fronts for all configurations in each waste evolution scenario are presented in Figure 5-5. For sake of clarity, the three configurations are only presented for the BAU scenario in order to rank the different solutions. Configuration A (the less constrained) leads to the solutions represented by the whole Pareto front, while the two other configurations (I and O) lead to some portions of the Pareto front. Obviously, in an open structure, there is a combination of all the available options. In Pareto front of configuration A, three parts can be determined based on the similarity of the three Pareto fronts of the three structures, like in BAU scenario (Figure 5-5).

The different configurations highlight three sections on the Pareto front following the COST increase:

- Part 1 corresponds to a combination of use of Non Recovery techniques and of existing recycling sites. Positive GWP impacts are obtained due to the selection of Non Recovery techniques. These techniques, despite their local availability, have no significant difference in treatment cost with the existing recycling sites.

- Part 2 involves a strong reduction of GWP while COST exhibits a nearly constant value from partial Non recovery to full recovery choice in the existing recycling sites. This sharp reduction of GWP impacts is observed in parallel with a light COST increase from 0.87 to 1.0 M€ in the BAU, similarly to the trend observed in Chapter 4, (Figure 5-5). For all the obtained solutions, all wastes in the system are recycled completely by the existing sites. The solutions given by configuration O are included in this section.

- Part 3 includes the configuration solutions where the existing recovery sites are used as well as the deployed sites. The open configuration A needs to create new recycling sites to reduce GWP impacts that existing recycling techniques and capacity (configuration O) cannot reach. The level of the gap between GWPmin in configuration A (GWP_{minA}) and GWPmin in configuration O (GWP_{minO}), calculated by this formula:

  $$\frac{GWP_{\min A} - GWP_{\min O}}{\left|GWP_{\min O}\right|} \times 100$$

  varies from (20) – (21) % in BAU, Light Decrease, and Strong Decrease to (82) % in Strong Increase (Table 5-4). The establishment of new recycling sites is especially important in the Increase Trends since it allows reducing important GWP impacts (Figure 5-6). The combined utilisation of existing sites and deployed sites allows reducing COST of configuration A compared to the one of configuration I for the same value of GWP. When looking deeper at the results of this section, it can be observed that microwave technique (not already present in the existing system) is deployed firstly in section 3 followed by SCW technique. Both configurations I and A have the same value of GWPmin which corresponds to the decentralisation of recovery sites at all waste sources with a zero value of transport cost.

The integration of all options in configuration A helps the system to take advantages of each option, i.e. obtaining a lower cost than with configuration I at the same GWP impacts and reaching lower GWP impacts than with configuration O. Therefore, the Pareto front of configuration A is constituted by a so-called "extension" of the Pareto fronts of the other configurations with more points corresponding to lower COST and lower GWP, for example in BAU (Figure 5-5) and Strong Increase (Figure 5-6).

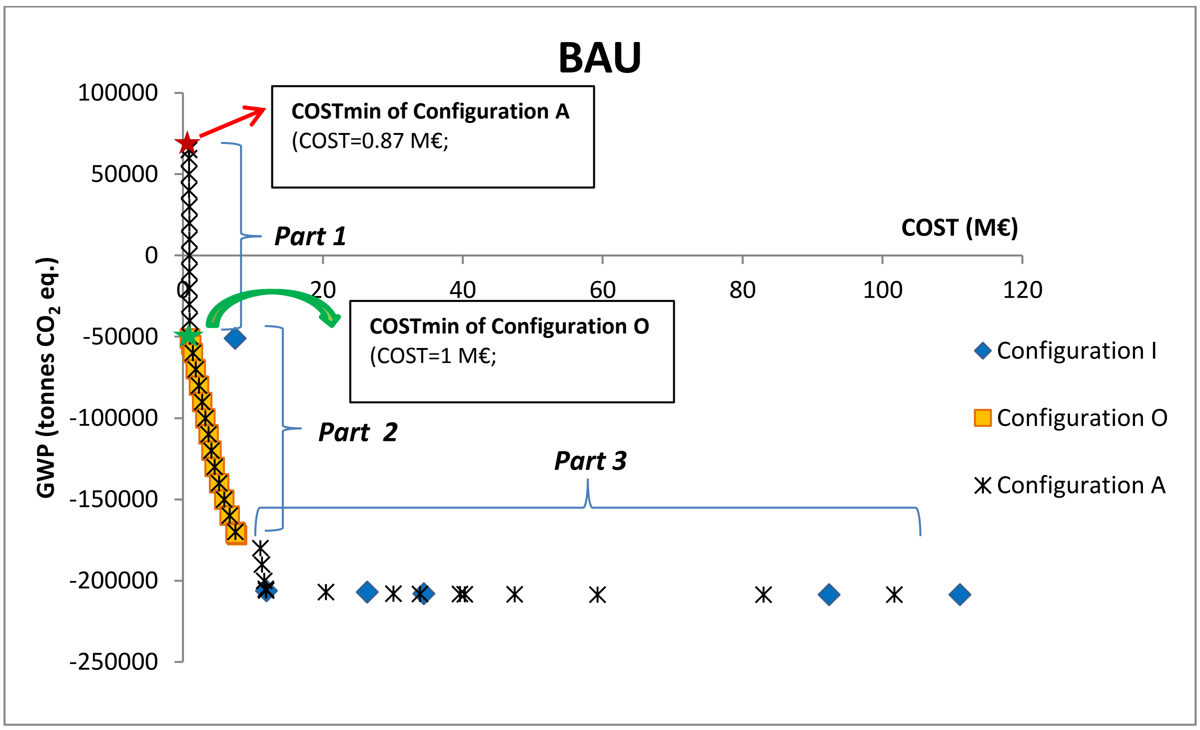


Figure 5-5: Pareto fronts of the three configurations (O, I and A) in BAU

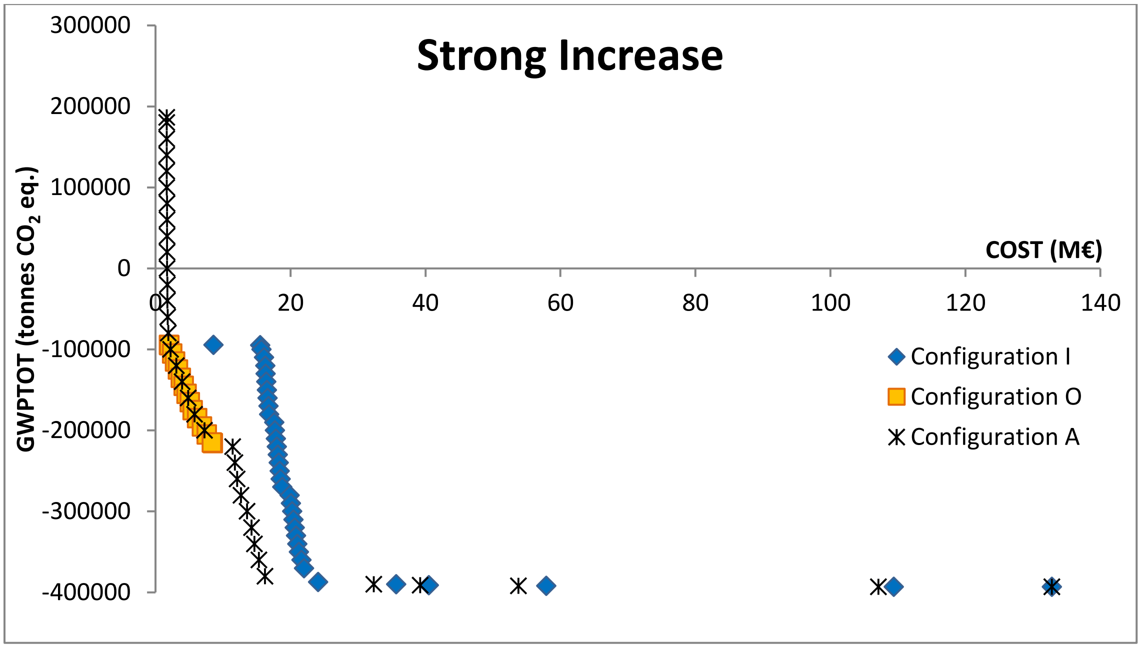


Figure 5-6: Pareto fronts of the three configurations (O, I and A) in Strong Increase

Table 5-4: GWPmin of configuration O and configuration A in Waste scenarios

Waste scenario	GWP_{minO} (tonnes CO_2 eq.)	GWP_{minA} (tonnes CO_2 eq.)	$\frac{GWP_{\min A} - GWP_{\min O}}{\lvert GWP_{\min O} \rvert} \times 100$ (%)
BAU	-171 996	-208 618	-21
Strong Increase	-215 743	-393 066	-82
Light Increase	-186 894	-281 591	-51
Light Decrease	-162 214	-194 717	-20
Strong Decrease	-65 949	-79 703	-21

5.4.2.3. Ranges of prices for recovered fibre

Different ranges of sales price of recovered fibre have been determined from the average cost price of recovered fibre. Four types of recovered products from Fibre-recovery pathways are considered as already taken into account in Chapter 4: fibre ($p=1$), powder ($p=2$), fibrous ($p=3$) and oligomer ($p=4$).

Fibrous is the rich-fibre part from grinding which generates also powder, a rich-matrix by-product. Due to the presence of impurity in fibrous, this product is not modelled as recovered fibre but is separated into another category of recovered products. Consequently, recovered fibres are obtained by the pre-treatment of dry fibre waste and by recycling techniques except from grinding. Although the quality of recovered fibre may vary according to the selected technique, the variation is relatively low and the quality of recovered fibres is close to more than 80 % of quality of virgin fibre (Chapter 1, Table 1-6). This explains why the difference in quality of recovered fibres from different techniques is not taken into account in the estimation of average cost price of recovered fibre. Besides, arbitrarily, the value of fibrous (*p=3*) is assumed to reach only half the value of recovered fibre. Due to the strong difference in use and in material nature, other recovered products, i.e. powder (*p=2*) used as fillers, and oligomers (*p=4*) used as fuels or chemical synthesis, are not considered in the estimation of average price for recycled fibre. The average cost price for recovered fibre (CUF) is calculated by dividing the total cost of the system by the amount of recovered fibre and the half of amount of fibrous (5.74).

$$CUF = \frac{COST}{QP_{p=1} + \frac{QP_{p=3}}{2}} \tag{5.74}$$

With

$$QP_{p=1} = \sum_{w\in\mathscr{W}} \sum_{i\in\mathscr{I}} \sum_{r\in\mathscr{R}} \sum_{c\in\mathscr{C}} \sum_{t\in\mathscr{T}} \sum_{l,l'\in\mathscr{L}} \begin{pmatrix} FPOPR_{wrctll'}^{p=1} + FPODR_{wrctll'}^{p=1} + FPOIR_{irctll'}^{p=1} + \\ +FPIPR_{wrctll'}^{p=1} + FPIDR_{wrctll'}^{p=1} + FPIIR_{irctll'}^{p=1} \end{pmatrix}$$

$$QP_{p=3} = \sum_{w\in\mathscr{W}} \sum_{i\in\mathscr{I}} \sum_{r\in\mathscr{R}} \sum_{c\in\mathscr{C}} \sum_{t\in\mathscr{T}} \sum_{l,l'\in\mathscr{L}} \begin{pmatrix} FPOPR_{wrctll'}^{p=3} + FPODR_{wrctll'}^{p=3} + FPOIR_{irctll'}^{p=3} + \\ +FPIPR_{wrctll'}^{p=3} + FPIDR_{wrctll'}^{p=3} + FPIIR_{irctll'}^{p=3} \end{pmatrix}$$

Following this principle, CUF is calculated for each point of the Pareto front of configuration A in each scenario (Table 5-5). In all waste scenarios, the decrease in GWP impacts also results in an increase in CUF. Table 5-5 presents the results of CUF at the minimum COST (COSTmin), the minimum GWP (GWPmin), M-TOPSIS solution and various solutions on Pareto front with the ratio of their GWP to GWPmin.

Due to the high quantity of recycled fibre obtained from large wastes, CUF at GWPmin in Increase trend scenarios are lower than in Decrease trend: the more quantity of recycled fibre, the less CUF is obtained according to the aforementioned scenarios. The reference prices of different fibres can be found in Chapter 3, Section 3.3.1.

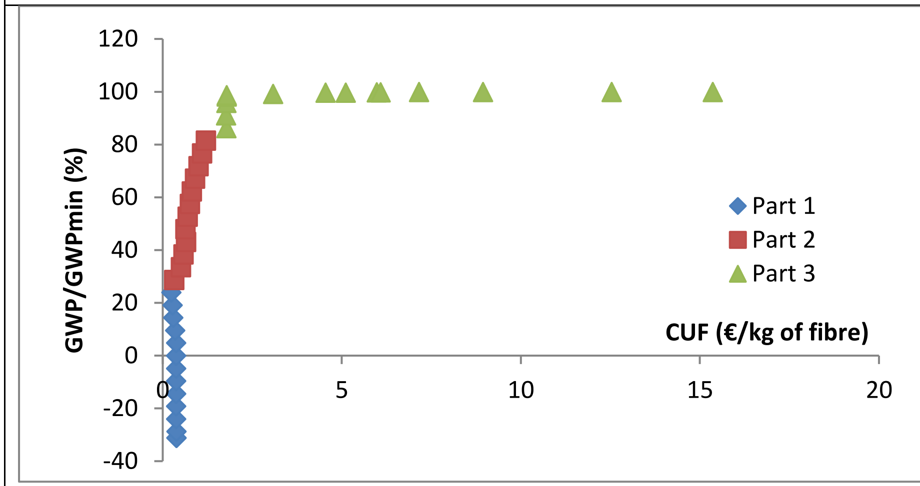
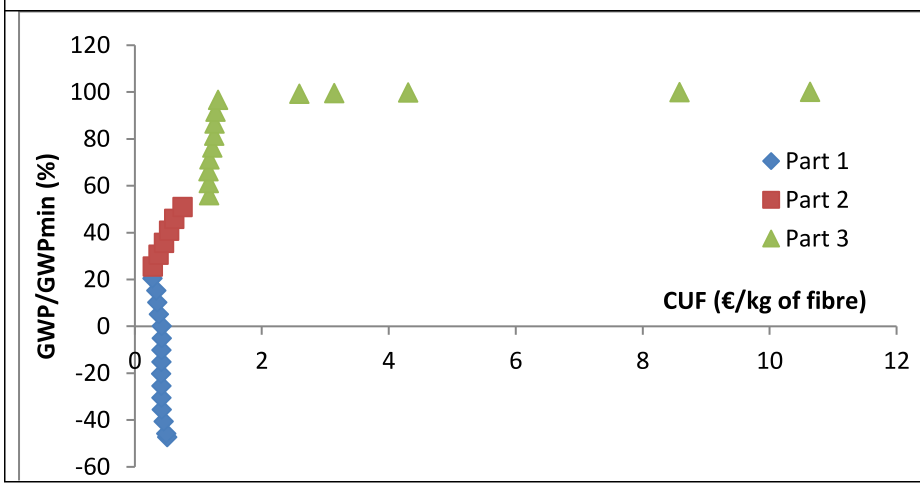
The complete decentralisation of recovery system at GWPmin makes the values of CUF more than 10 €/kg, up to 37 €/kg in Strong Decrease due to the important investment cost. These values are close to the price of virgin carbon fibres (see Chapter 3) so that it may be difficult for recovered fibres to break into the market. Furthermore, CUF at 99%GWPmin in all waste scenarios is lower than 4.5 €/kg which is the minimum sales price for low-cost carbon fibre (Berreur et al., 2002). A value of around 2 €/kg for CUF may be profitable for 99%GWPmin in other waste scenarios, except for Strong Decrease. Therefore, the configuration of the system at GWPmin seems not profitable for reutilisation of recycled fibre without subsidies.

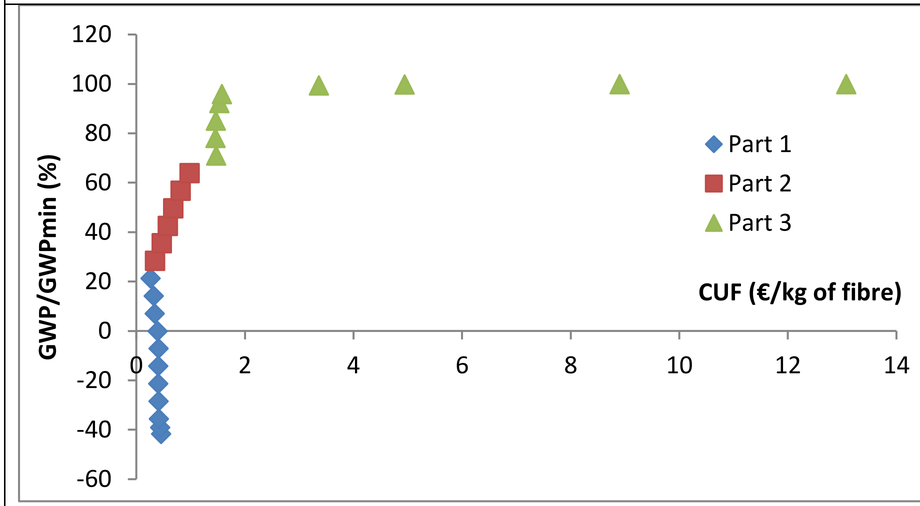
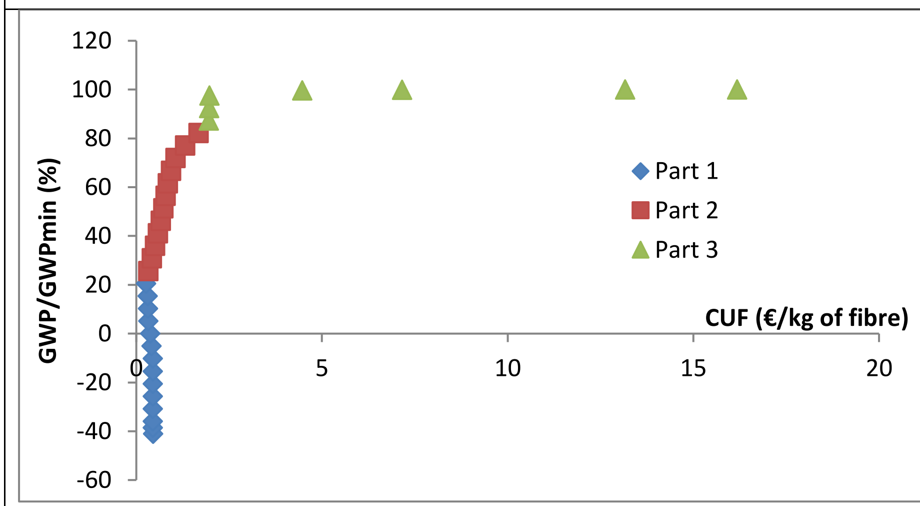
Without the pressure of overflow of waste input in the first ten years of the horizon time, there is no deployment of new recovery sites at COSTmin which offers an attractive range of cost price for substitution of low-value fibre like glass fibre since CUF in waste scenarios are all under 1 €/kg which is the minimum price of virgin glass fibre for general use (Dupupet, 2008).

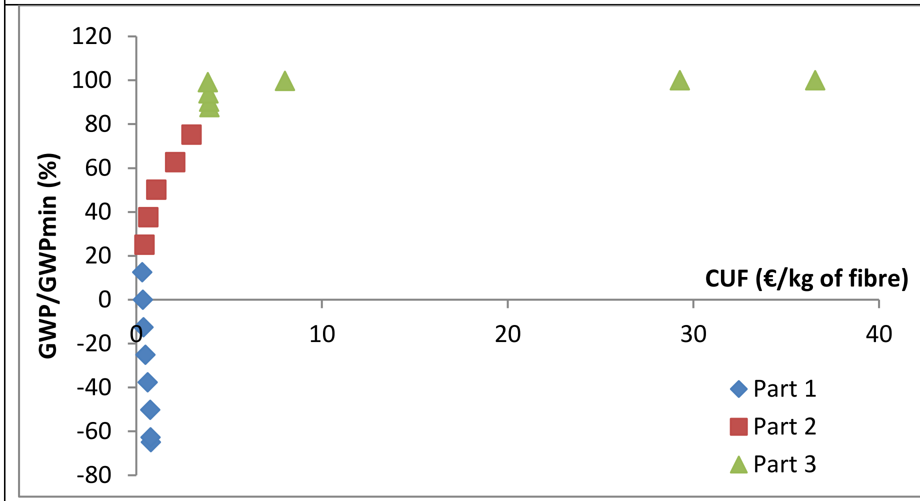
It is important to note that these results show the suitable conditions for deployment of new recycling sites. Indeed, the deployment is pulsed only by the objective of GWP minimisation when CUF is more than 1.2 €/kg in Strong Increase scenario and up to 4 €/kg in Strong Decrease scenario. The deployment begins at more than 55%GWPmin in Strong Increase, 67%GWPmin in Light Increase and 83% in BAU and Decrease Trend scenarios. The deployment in configuration A corresponds to part 3 in Pareto front (see Table 5-5).

However, the bi-criteria COST-GWP optimisation in this step does not consider the impact of the variation of monetary value over time and the differences in quality of recovered fibres from each recycling technique for economic assessment. The next step will overcome these limitations by introducing a new objective function based on the maximisation of NPV.

Table 5-5: GWP/GWPmin (%) vs. CUF and several values of CUFfor points in Pareto front in configuration in waste scenarios (*: deployment needed)

<table>
<tr><th></th><th>Point in Pareto front of</th><th>CUF (€/kg of fibre)</th></tr>
<tr><td colspan="3">BAU scenario</td></tr>
<tr><td rowspan="9">
</td><td>GWPmin</td><td>15.36 (*)</td></tr>
<tr><td>99% GWPmin</td><td>1.97 (*)</td></tr>
<tr><td>98% GWPmin</td><td>1.79 (*)</td></tr>
<tr><td>95% GWPmin</td><td>1.78 (*)</td></tr>
<tr><td>90% GWPmin</td><td>1.77 (*)</td></tr>
<tr><td>80% GWPmin</td><td>1.18</td></tr>
<tr><td>50% GWPmin</td><td>0.66</td></tr>
<tr><td>COSTmin</td><td>0.38</td></tr>
<tr><td>M-TOPSIS</td><td>1.21</td></tr>
<tr><td colspan="3">Strong Increase scenario</td></tr>
<tr><td rowspan="8">
</td><td>GWPmin</td><td>10.64 (*)</td></tr>
<tr><td>99% GWPmin</td><td>1.92 (*)</td></tr>
<tr><td>98% GWPmin</td><td>1.33 (*)</td></tr>
<tr><td>95% GWPmin</td><td>1.29 (*)</td></tr>
<tr><td>90% GWPmin</td><td>1.27 (*)</td></tr>
<tr><td>80% GWPmin</td><td>1.25 (*)</td></tr>
<tr><td>50% GWPmin</td><td>0.73</td></tr>
<tr><td>COSTmin</td><td>0.51</td></tr>
</table>

<table>
<tr><td></td><td>M-TOPSIS</td><td>1.27 (*)</td></tr>
<tr><td colspan="3">Light Increase scenario</td></tr>
<tr><td rowspan="9">
</td><td>GWPmin</td><td>13.08 (*)</td></tr>
<tr><td>99% GWPmin</td><td>1.74 (*)</td></tr>
<tr><td>98% GWPmin</td><td>1.63 (*)</td></tr>
<tr><td>95% GWPmin</td><td>1.57 (*)</td></tr>
<tr><td>90% GWPmin</td><td>1.50 (*)</td></tr>
<tr><td>80% GWPmin</td><td>1.46 (*)</td></tr>
<tr><td>50% GWPmin</td><td>0.69</td></tr>
<tr><td>COSTmin</td><td>0.46</td></tr>
<tr><td>M-TOPSIS</td><td>1.53 (*)</td></tr>
<tr><td colspan="3">Light Decrease scenario</td></tr>
<tr><td rowspan="9">
</td><td>GWPmin</td><td>16.18 (*)</td></tr>
<tr><td>99% GWPmin</td><td>2.00 (*)</td></tr>
<tr><td>98% GWPmin</td><td>1.98 (*)</td></tr>
<tr><td>95% GWPmin</td><td>1.97 (*)</td></tr>
<tr><td>90% GWPmin</td><td>1.96 (*)</td></tr>
<tr><td>80% GWPmin</td><td>1.53</td></tr>
<tr><td>50% GWPmin</td><td>0.71</td></tr>
<tr><td>COSTmin</td><td>0.46</td></tr>
<tr><td>M-TOPSIS</td><td>1.97 (*)</td></tr>
</table>

<table>
<tr><th colspan="3">Strong Decrease scenario</th></tr>
<tr><td rowspan="9">
</td><td>GWPmin</td><td>36.56 (*)</td></tr>
<tr><td>99% GWPmin</td><td>3.86 (*)</td></tr>
<tr><td>98% GWPmin</td><td>3.87 (*)</td></tr>
<tr><td>95% GWPmin</td><td>3.88 (*)</td></tr>
<tr><td>90% GWPmin</td><td>3.92 (*)</td></tr>
<tr><td>80% GWPmin</td><td>3.27</td></tr>
<tr><td>50% GWPmin</td><td>1.06</td></tr>
<tr><td>COSTmin</td><td>0.79</td></tr>
<tr><td>M-TOPSIS</td><td>3.86 (*)</td></tr>
</table>

5.4.3. NPV-GWP Optimisation

5.4.3.1. Bi-criteria optimisation

In this step, an economic assessment is carried out by the maximisation of NPV (Net Present Value) while environmental impacts are minimised through GWP on a 20-year horizon time.

In the previous section, it has been shown that, according to the existing recovery capacity, the deployment is only necessary during the second ten-year period of Strong Increase for full recovery. Consequently, the possibility of deployment for each year will not be considered during optimisation in order to shorten computational times. Indeed, in the ten-year lifespan for each new recycling site, the decision for deployment will be made during the year 0 or during the year 10.

Different prices for recovered fibre (RCF price) have been considered: 0.25; 1; 2; 3; 4.5 €/kg of fibre, so that they remain competitive with other fibres (Chapter 3, Section 3.3.1). In comparison, the lowest value, i.e. 0.25 €/kg (Job, 2013), corresponds to the price of recycled glass while the highest price, i.e. 4.5 €/kg, is the minimum price for low-cost carbon fibre (Chen, 2014). The results obtained in COST-GWP optimisation in Section 5.4.2 show that the price of 1 €/kg of fibre can be profitable for the existing system without deployment while the deployment of new recycling sites requires a price around 2 and 3 €/kg of fibre.

The profit from the other recovered products is included in the NPV of the system with the fixed prices for their applications (see Chapter 3): 0.091 €/tonne for powder (used as limestone); and 1.52 €/kg for oligomers. Similarly to the preceding section, fibrous, which is the main product of grinding, is assumed to have half value of recycled fibre.

In each waste scenario, the Pareto fronts for every fixed price of recovered fibre have been obtained through ε-constraint method by maximising NPV for successive intervals of GWP. The dominant point in the Pareto front is also observed in the NPV-GWP optimisation as with the COST-NPV optimisation in the precedent section, especially for high RCF prices, i.e. 3€/kg and 4.5 €/kg.

5.4.3.2. Pareto front of Bi-criteria Optimisation (GWP – NPV)

Figure 5-7 represents the Pareto fronts of BAU scenario for different RCF prices. Several observations can be made: in each waste scenario, the increase in RCF price leads to a more and more reduced number of points in the Pareto front. Indeed, following the increase in RCF price, the maximum NPV (NPVmax) increases while the minimum GWP (GWPmin) remains constant for different RCF prices. Besides, following the same trend, GWP at NPVmax (GWP-N) is reduced via the increase in recovered products whereas NPV at GWPmin (NPV-G) rises, such as in BAU scenario for example (Figure 5-7). GWP-N can be thus closer to GWPmin clearly from 0.25 €/kg to 4.5 €/kg of RCF prices.

The M-TOPSIS method is used to determine the compromise solution for two considered objectives. In this bi-criteria optimisation, the position of M-TOPSIS solutions of each waste scenario compared to the extreme solutions, i.e. GWPmin and NPVmax, with different fixed RCF prices can be observed in Figure 5-8 for GWP at M-TOPSIS point and GWPmin; respectively in Figure 5-9 for NPV at M-TOPSIS point and NPVmax. GWP of M-TOPSIS solutions are very close to the value of GWPmin, the gap between NPV and NPVmax varies largely on the RCF prices.

GWP of M-TOPSIS solutions are very close to the value of GWPmin. Indeed, the gap between two values is from around 7% of GWPmin in Light Increase scenario to lower than 1% of GWPmin in Strong Decrease scenario. The effect of RCF prices on GWP of M-TOPSIS solutions is not clear as M-TOPSIS ranking depends on the density of available Pareto optimal solutions.

Otherwise, for economic aspect, the gap between NPV of M-TOPSIS solutions and NPVmax is varied in function of the RCF prices. Indeed, this gap is important at the low RCF prices, i.e. 0.25 and 1 €/kg. However, it is reduced progressively with the increase of total waste quantity and the augmentation of RCF price, from around (6000) % of NPVmax at Strong Decrease scenario with RCF price of 0.25 €/kg in which in one hand the waste quantity is so small and the RCF price is lowest in the studied range in another hand, to (7) % of NPVmax at Strong Increase scenario with RCF price of 4.5 €/kg which in contrast has important waste quantity and high RCF price.

Therefore, the setting of RCF prices has important impacts on the optimisation of both NPV and GWP via the variation of GWP-N but they need to be low enough to be competitive with other fibres. The difficulty is how to select an appropriate value of RCF price while the market of recovered fibre can extend from substitution of low-value fibre with low profit to higher value applications through new recycling techniques and conditioning.

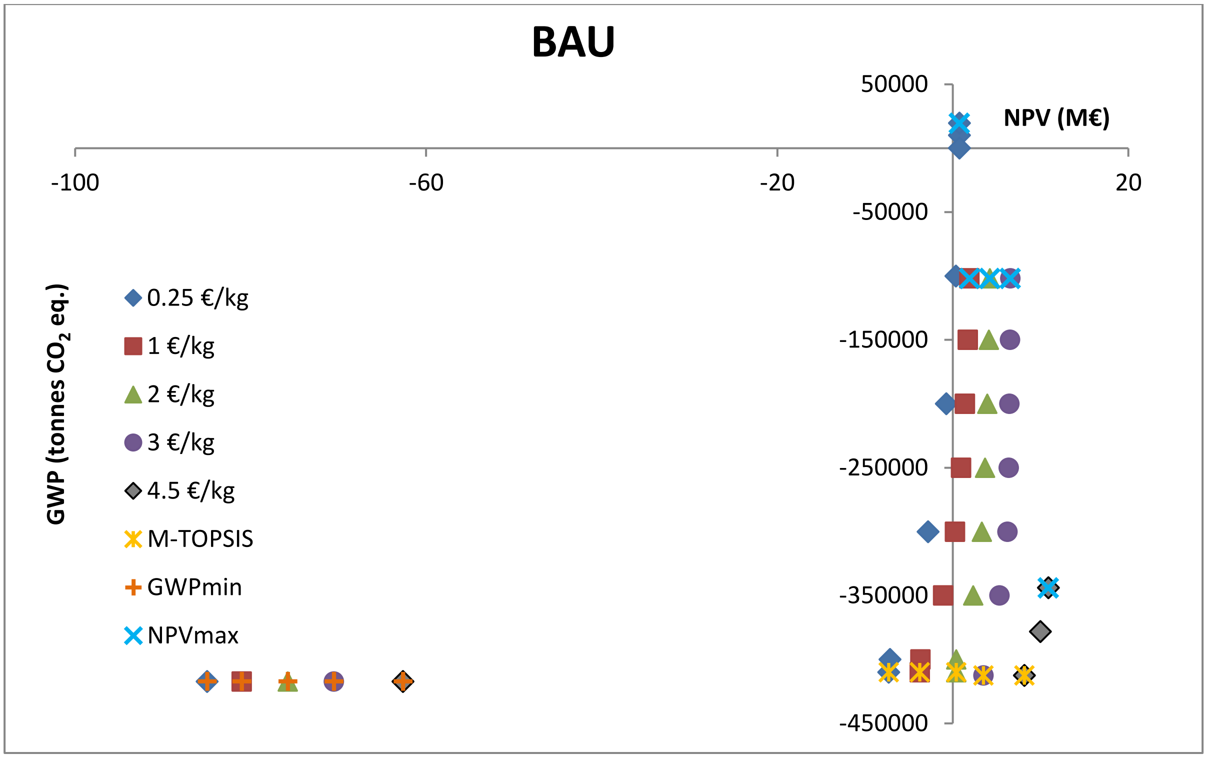


Figure 5-7: Pareto fronts for NPV-GWP of RCF prices in BAU

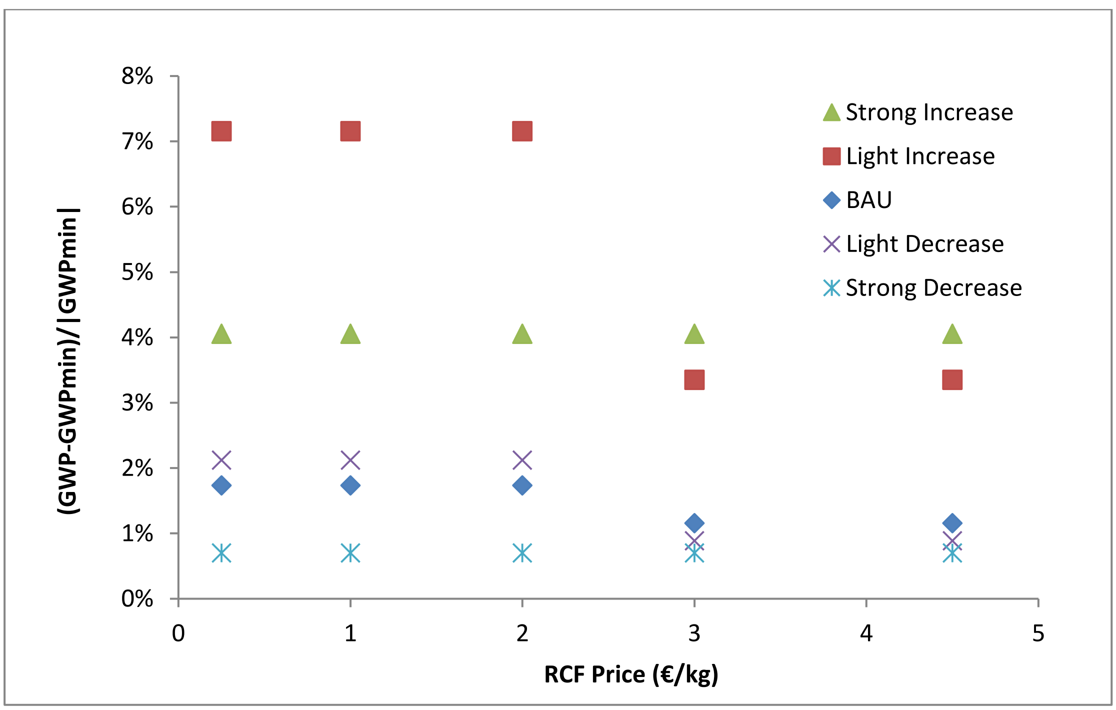


Figure 5-8: The different ratio of GWP in M-TOPSIS point to GWPmin for each RCF price scenario in all waste scenarios

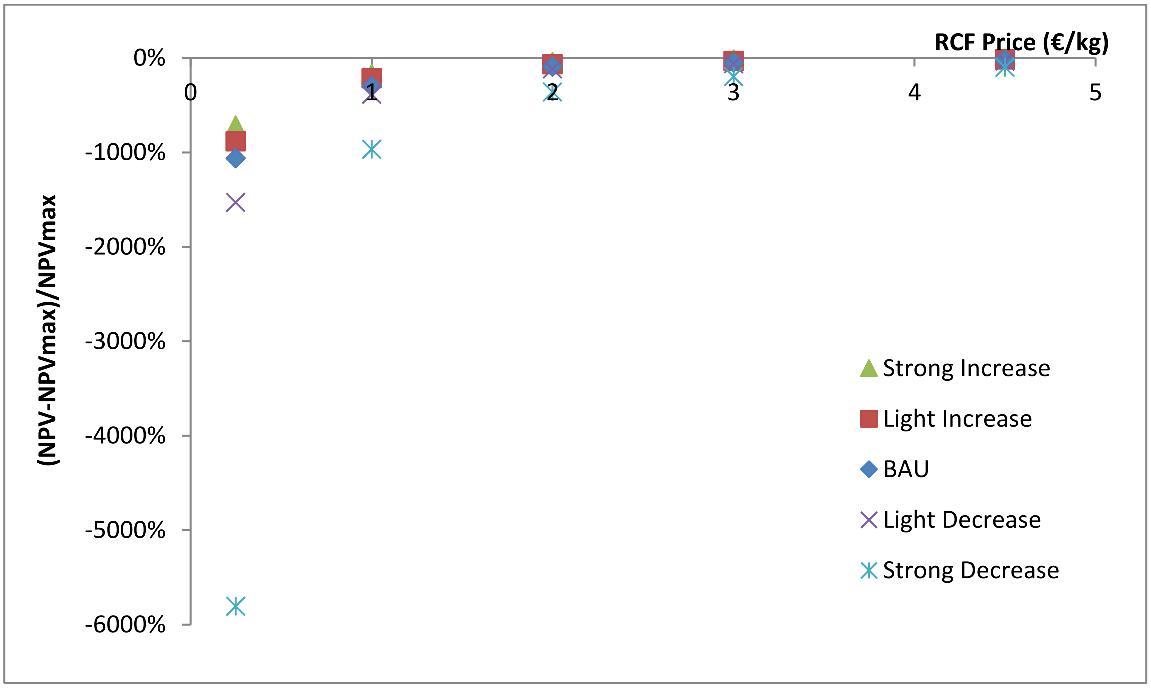


Figure 5-9: The different ratio of NPV in M-TOPSIS point to NPVmax for each RCF price scenario in all waste scenarios

5.4.3.3. Configuration corresponding to GWPmin

As it was shown in Figure 5-7, the value of GWPmin of each waste scenario is independent on the imposed prices of RCF. Each waste scenario has a unique GWPmin value that corresponds to a common configuration of waste management for all prices of RCF which will be presented in detail in this section.

With the lexicographic method, the point of GWPmin in the Pareto front has the maximum NPV value for each RCF fibre. As the range of RCF prices imposed in the system is below the CUF (10.64 – 36.56 €/kg) for GWPmin found in step 1, i.e. Minimisation of COST-GWP in Section 5.4.2, the value of NPV at GWPmin in all waste scenarios are always negative. However, the loss of NPV at GWPmin decreases with RCF price increase. These configurations represent the same strategy of decentralisation at GWPmin with step 1. The waste distribution in recovery pathways and the deployment of recycling plants in each waste scenario of GWPmin configuration are mapped in Figure 5-10. Several observations for this configuration can be made:

– The optimal configuration shows that all wastes are recycled on-site; therefore, no transport cost is considered. Two techniques are favoured in the system for recycling process, i.e. microwave and supercritical water. Microwave recycling is used to treat end-of-life waste, while supercritical water allows recycling uncured and cured production wastes. The other techniques in the existing sites receive only dry fibre waste for pre-treatment step.

– In Strong Increase scenario, deployment of new sites occurs both in year 0 and year 10 due to the high increase in production wastes. Instead of full investment in year 0, the investment on supercritical water sites occurs in year 10 (taking advantage of a discount rate of 10%/year) while the waste overflow occurs in the second ten years in the horizon time.

– Despite the difference of waste evolution, both Light Decrease and Strong Decrease have the same deployment of techniques and capacities as BAU scenario with the smallest capacities of microwave and supercritical water. The similar configuration in these scenarios is due to the fixed the capacity considered for each scale (small, medium, large) (see Section 5.2.2) that total quantity of wastes generated is all under the smallest capacity.

– Due to the constraints on capacity for all scenarios, the deployed sites largely operate at under-capacity, at only 1.3-8 % of their capacity for supercritical water in Strong Decrease for example. For the Decrease trend in waste evolution, the scale of recycling techniques should be adapted to the waste quantity generated in the system to reduce the cost of investment and improve recycling productivity.

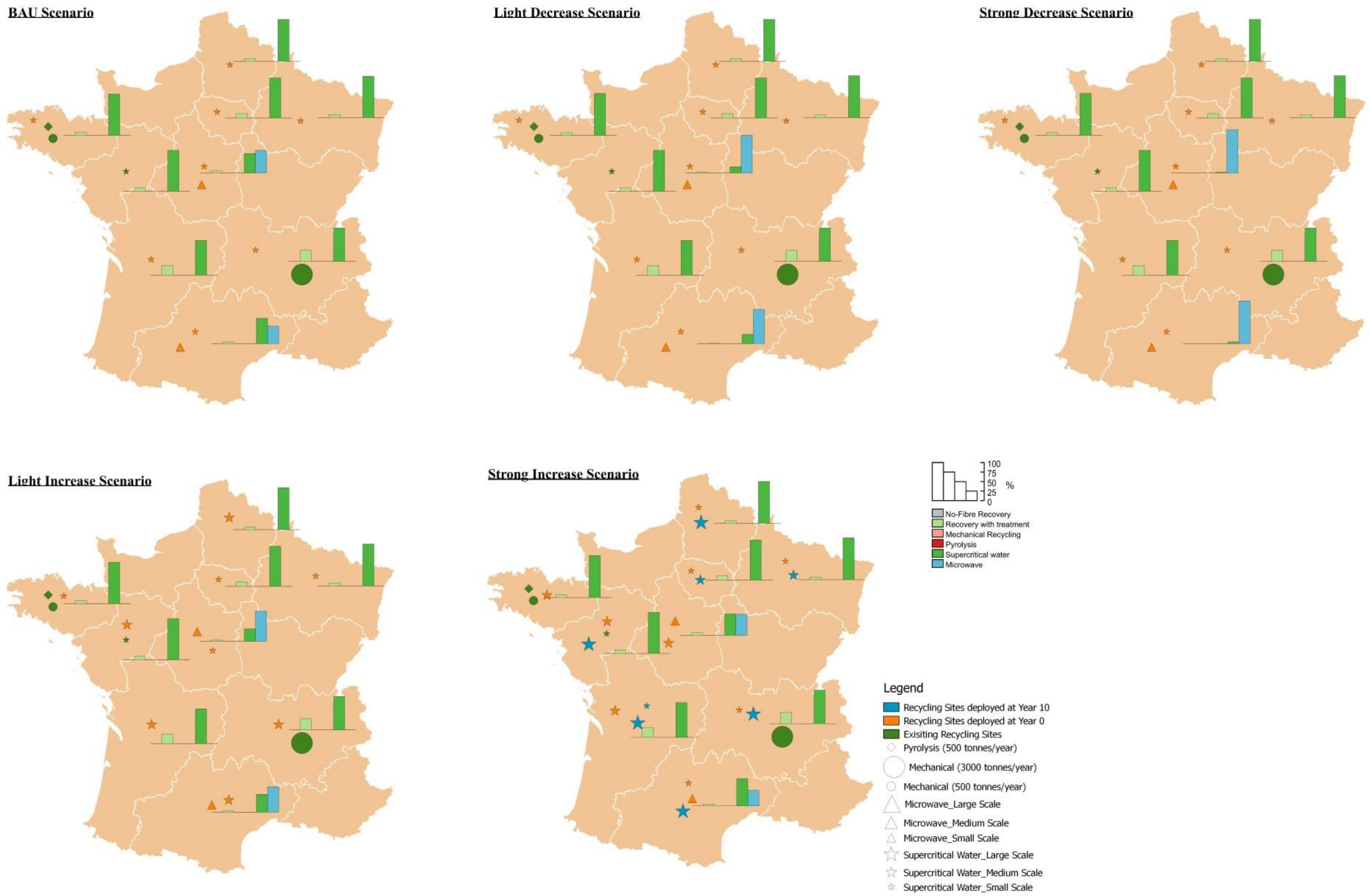


Figure 5-10: Snapshot of GWPmin configuration in the studied waste scenario

5.4.3.4. Configuration corresponding to NPVmax

Waste distributions in deployed recycling plants (***FWRI***), existing recycling plant (***FWRO***) and No-fibre recovery routes (***FWNR***) at the maximum NPV (NPVmax) for each RCF price in the different scenarios are summarised in Figure 5-11.

The value of NPVmax increases with RCF price and waste quantity. In all waste evolution scenarios, a positive value of NPV can be obtained even if the recovered carbon fibre is sold at the price of recycled glass fibre (0.25 €/kg). However, at that low price, all wastes generated cannot be recycled completely. Indeed, more than 80 % of wastes in Strong Increase and BAU are incinerated. The proportion of wastes sent to Non Recovery pathways (FWNR) is reduced with the decrease in waste quantity, to around 20 % in Strong Decrease. Finally, when small waste quantities are involved, the proportion of waste going to Non recovery pathways is reduced in order to maximise the profit of recovered fibre. When a high quantity of waste is considered, more wastes are incinerated to reduce transport cost and recycling treatment. Indeed, in this case, the recycling of large quantity of waste cannot be compensated by the low price of recovered fibre. Besides the reduction of wastes in the system, the increase in RCF prices avoids the utilisation of Non recovery routes.

Although Strong Increase scenario needs an extension of recycling capacity for full recovery, new recycling sites can be deployed in this scenario only from a RCF price high enough to make profit, i.e. 2 €/kg which agrees with the estimation of CUF in the previous section. For other waste scenarios which do not need deployment due to the overflows of wastes, even with RCF price up to 4.5 €/kg, there is no economic interest in the system to deploy new recycling techniques like microwave.

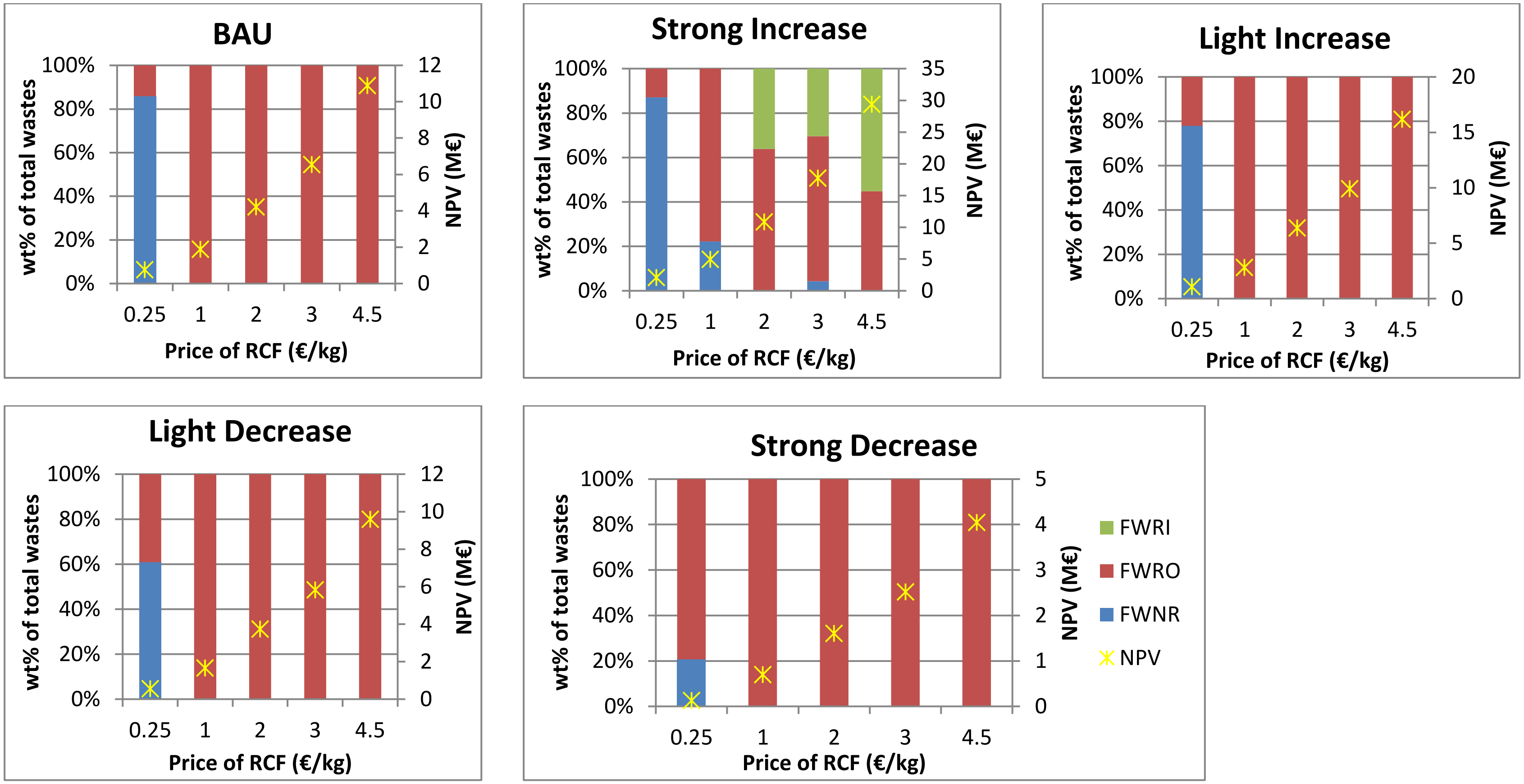


Figure 5-11: Waste distributions (FWRI: Flow of Wastes to Deployed Recovery Sites; FWRO: Flow of Wastes to Existing Recovery Sites; FWNR: Flows of Wastes to Non-Recovery Paths) and NPV for each RCF price of waste scenarios

5.4.3.5. Multi-criteria decision making with PROMETHEE approach

Three criteria are considered in PROMETHEE evaluation: minimisation of price (Price) for recovered fibre, maximisation of NPV (NPV) and minimisation of GWP (GWP). The weights are distributed among the three criteria following two distinct strategies:

- The first one proposes that all criteria are on a same basis. In this case, the same weights are attributed to all the criteria.

- As price and NPV criteria both represent the economic objective whereas GWP refers to an environmental component, the weights distributed on Price-NPV-GWP in the second strategy are 1-1-2.

The values of Price, NPV and GWP at GWPmin, NPVmax and M-TOPSIS of all RCF prices are evaluated under these two strategies. Figure 5-12 shows the positions of these points on 2D view of GAIA surface (For price n°1: 0.25 €/kg; 2: 1 €/kg; 3: 2€/kg; 4: 3€/kg; 5. 4.5 €/kg: For NPVmax – N; For GWPmin – G; For M-TOPSIS – T) in BAU scenario for example. The red line represents the decision axis whose direction and length vary in the function of the weights on each criterion.

The minimisation of RCF price reduces the profit of NPV (same observation as with GWP minimisation). Indeed, in the first strategy (weights: 1-1-1), the decision axis is directed on the opposite side of NPV criterion. The weight of NPV is reduced in the second strategy (weights: 1-1-2), the decision axis switches and fits on the GWP axis. Consequently, the 1st rank of PROMETHEE evaluation is GWPmin with a RCF price of 0.25 €/kg for both strategies of weighting. However, NPV at these points is always negative.

Therefore, the condition of positive NPV is added in PROMETHEE ranking in order to select the relevant solution for recyclers in different waste scenarios. The selected solution is the top rank one in the decreasing classification of PROMETHEE with positive NPV.

Table 5-6 shows the 1st rank of PROMETHEE with and without additional condition for two weight strategies in all scenarios. In each scenario, the two strategies lead generally to the same solution. When there are two solutions on the same rank, the common solution to both strategies has been chosen.

Table 5-7 presents the variation of annual cost, accumulated NPV (NPVTS) and annual GWP impacts from year 0 (the first year of deployment decision) to the year 20 of the solutions of two cases, i.e. with and without additional condition on positive NPV. The forms of cumulated NPV and total cost are in close relationship with the deployment decision. As investment cost is much more important than other operational cost, a strong increase in annual cost can be observed which corresponds to the deployment decision. Furthermore, the discontinuity of accumulated NPV reflects the transition between two deployment periods by addition of new capacity or new technique, clearly in Strong Increase scenario. Although annual GWP impacts depend on the availability of treatment techniques, they also logically vary in function of the quantity of wastes generated annually.

Generally, the M-TOPSIS solution is the first choice with the additional constraint of positive NPV in PROMETHEE ranking for all waste scenarios except for Strong Decrease scenario.

- Indeed, the M-TOPSIS point of Strong Decrease presents a negative NPV. The selected solution with the additional constraint of positive NPV in PROMETHEE is NPVmax with 1 €/kg of RCF price. In this scenario, the production wastes are reduced largely over time under environmental policy of waste producers and the shortage of production wastes which are cheaper to recycle than the end-of-life waste which increases over time. The strategy for the system in Strong Decrease therefore is to maximise profit margins with low price of recover fibre by using full capacity of the existing recycling sites without deployment. Although the GWP decrease in this strategy is lower than in the case of GWPmin, the system in Strong Decrease scenario does not suffer the pressure of important waste flows of for treatment, and recycled fibres are competitive in market with low sales price.

- The appropriate price for other wastes scenarios are within a medium range of 2 -3 €/kg. The Strong Increase leads to a lower price than with Light Increase and Light Decrease because of the high quantity of production wastes.

The snapshots of the whole project from the configuration of the solutions selected by the PROMETHEE evaluation with the supplement condition of positive NPV are illustrated from Figure 5-13 to Figure 5-17. Let us recall that the M-TOPSIS solutions are relevant for BAU, Strong Increase, Light Increase, Light decrease scenarios while NPVmax is selected for Strong Decrease scenario according to the PROMETHEE evaluation with the supplement condition of positive NPV. Some general observations of these configurations can be highlighted about the relevant solution for each waste scenario:

- In contrast to the decentralisation configuration at GWPmin, these configurations are all of centralised type in which there are few recycling sites in some regions and wastes of other regions need to be transported for recovery.

- In the configuration of the M-TOPSIS solutions, apart from Strong Increase scenario which requires increase capacity for waste overflows, deployment is also observed in the other waste scenarios though they do not have waste overflows. The objective is to improve both economic profit and reduce GWP impacts compared to the existing recycling sites: for this purpose, only microwave, which is not present yet in the existing recovery network, is deployed in the system. This technique has various advantages: end-of-life waste acceptability in process, reduced combustion and oligomer recovery compared to pyrolysis; cheaper treatment cost than supercritical water despite lower quality of fibre and lower recovery yield of oligomers; better recovery of fibre and oligomers than grinding. Therefore, in BAU, Strong Increase, Light Increase, Light Decrease scenarios, the dominant technique is microwave while the other recycling techniques are used for pre-treatment step and can alleviate the pressure on microwave capacity.

- As transportation plays important role in centralised system, the regions with huge waste quantity or close to waste sources constitute sources implementation of recycling sites. In this study, the first choice is ALPC region. Indeed, in the configurations with new recycling sites of M-TOPSIS solutions, microwave plants with the appropriate scales for waste scenarios are always built in ALPC. Only in Strong Increase scenario with overflows of wastes in the second ten-year, new recycling plants are implemented in PL and IDF for that period after the deployment in ALPC in year 0.
- Under capacity constraints, Light Decrease and BAU scenarios have the same configuration of waste distribution due to the smallest scale of microwave in these scenarios.

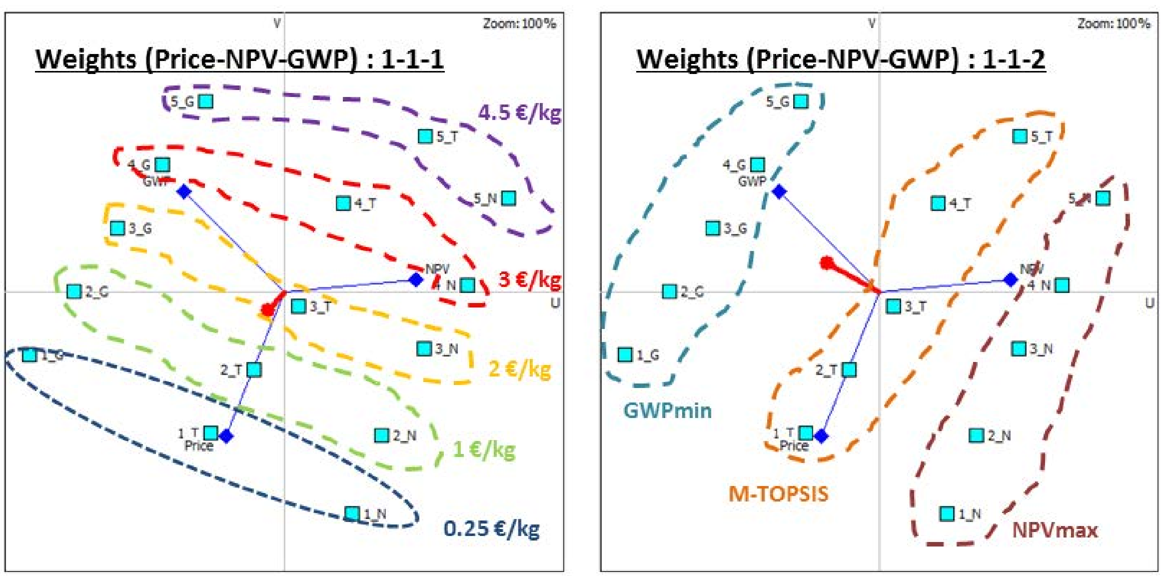
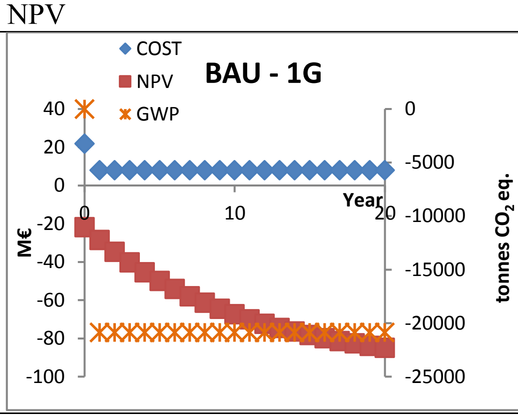
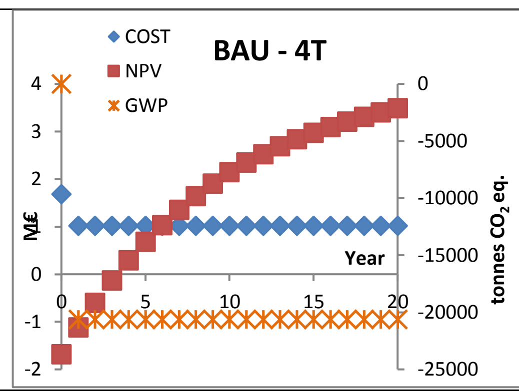


Figure 5-12: U-V views of GAIA Surface for BAU scenario with weights on Price-NPV-GWP: (left) 1-1-1 (U-V: 98%); (right) 1-1-2 (U-V: 98%) (For price – 1: 0.25 €/kg; 2: 1 €/kg; 3: 2€/kg; 4: 3€/kg; 5. 4.5 €/kg: For NPVmax – N; For GWPmin – G; For M-TOPSIS – T)

Table 5-6: 1st rank in PROMETHEE evaluation with and without additional constraint of positive NPV for 2 strategies of priority weight (For price – 1: 0.25 €/kg; 2: 1 €/kg; 3: 2€/kg; 4: 3€/kg; 5. 4.5 €/kg: For NPVmax – N; For GWPmin – G; For M-TOPSIS – T)

Waste Scenario	Weight			1st rank of PROMETHEE	
	Price	NPV	GWPTOT	Without additional constraint of positive NPV	With additional constraint of positive NPV
Strong Increase	1	1	1	1G, 1T	3T
	1	1	2	1G	3T
Light Increase	1	1	1	1G	4T
	1	1	2	1G	4T
BAU	1	1	1	1G	4T
	1	1	2	1G	4T
Light Decrease	1	1	1	1G	4T
	1	1	2	1G	4T
Strong Decrease	1	1	1	1G, 1T	1N, 2N
	1	1	2	1G	2N

Table 5-7: The variation of COST, NPV and GWP per year in the horizon time of the 1st rank in PROMETHEE evaluation PROMETHEE evaluation with and without additional constraint of positive NPV (For price – 1: 0.25 €/kg; 2: 1 €/kg; 3: 2€/kg; 4: 3€/kg; 5. 4.5 €/kg: For NPVmax – N; For GWPmin – G; For M-TOPSIS – T)

<table>
<tr><th>Waste Scenario</th><th>Without additional constraint of positive NPV</th><th>With additional constraint of positive NPV</th></tr>
<tr><td>BAU</td><td>
</td><td>
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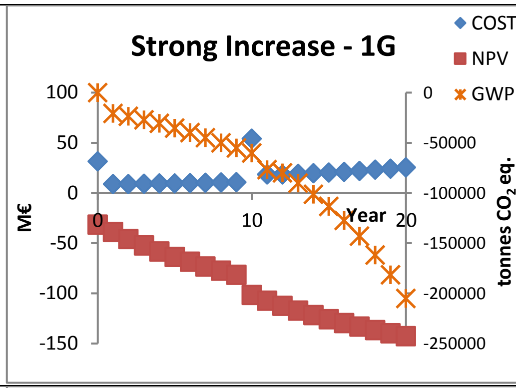
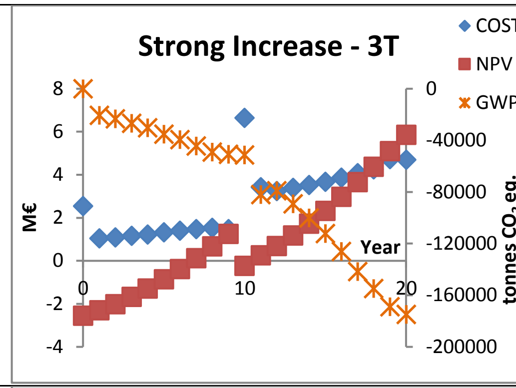
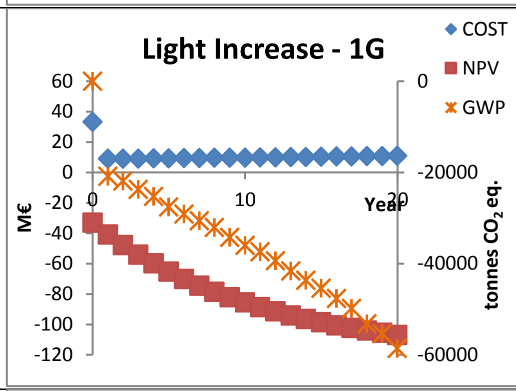
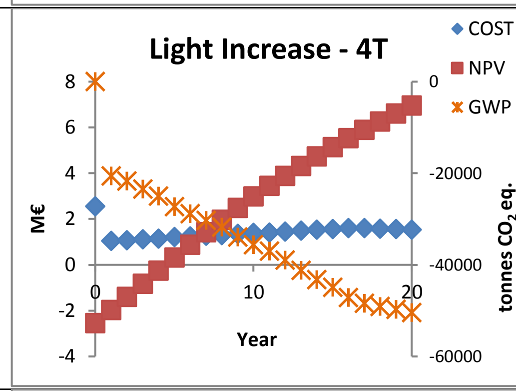
Strong Increase



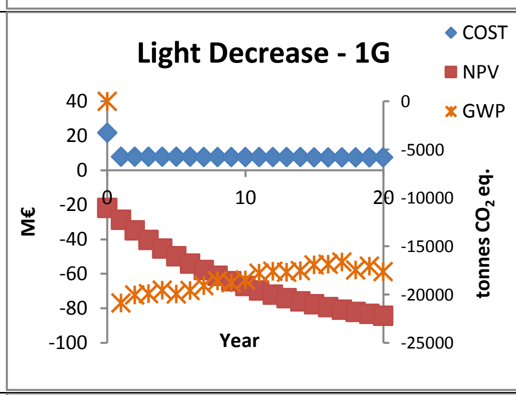


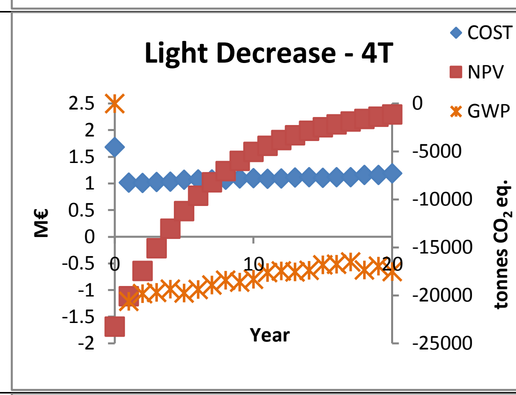
Light Increase



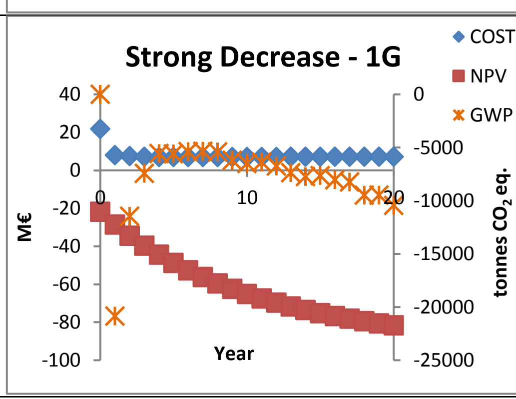


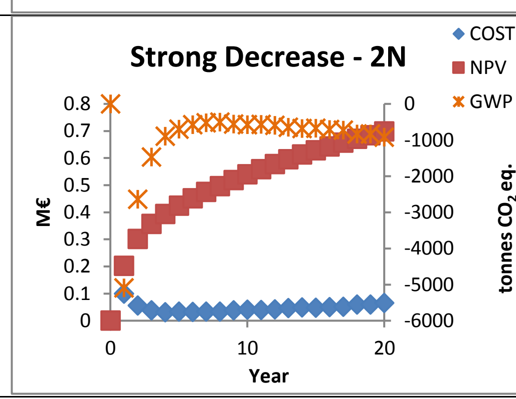
Light Decrease





Strong Decrease





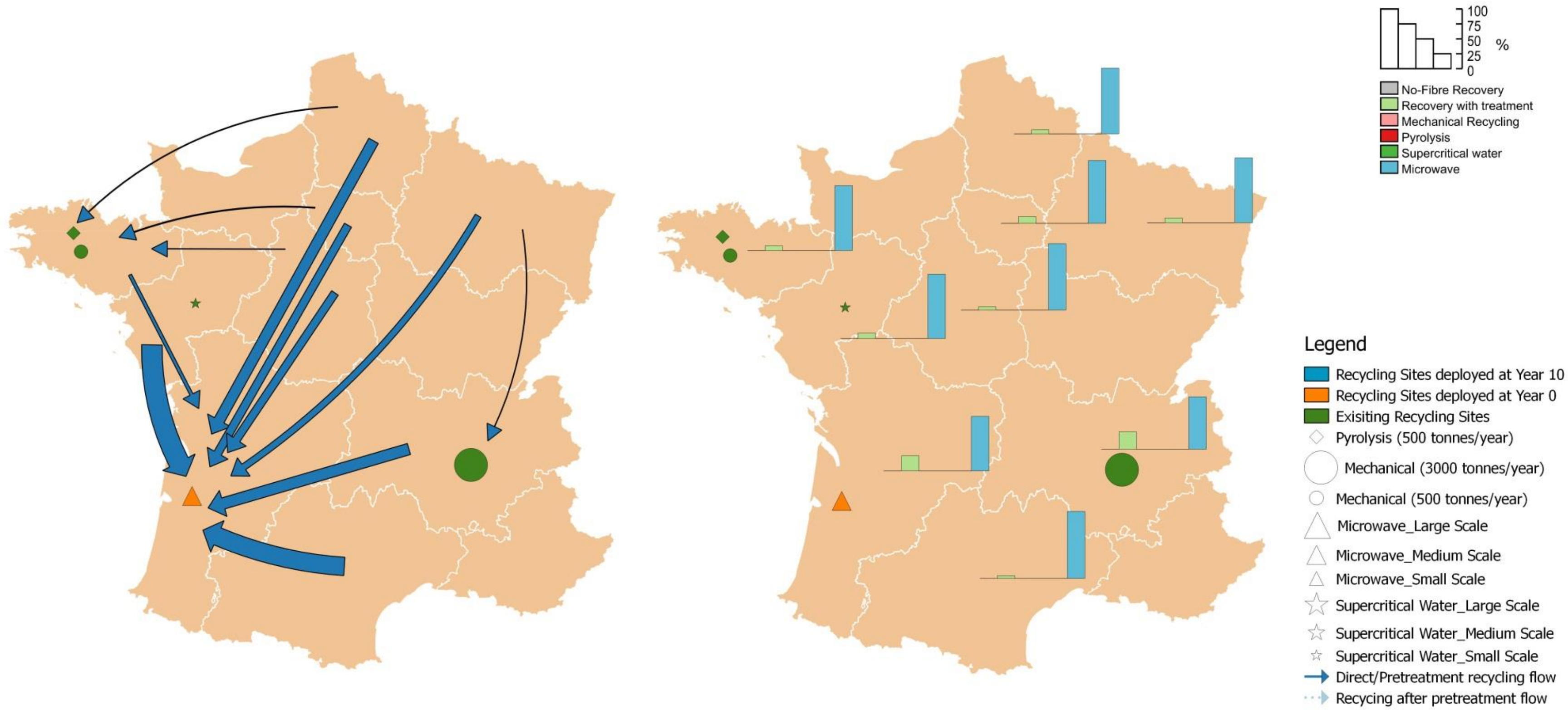


Figure 5-13: Snapshot of configuration for BAU-4T (M-TOPSIS point of 3 €/kg of fibre) of the whole horizon time: right. Waste flows; left. Waste allocation on waste treatment techniques

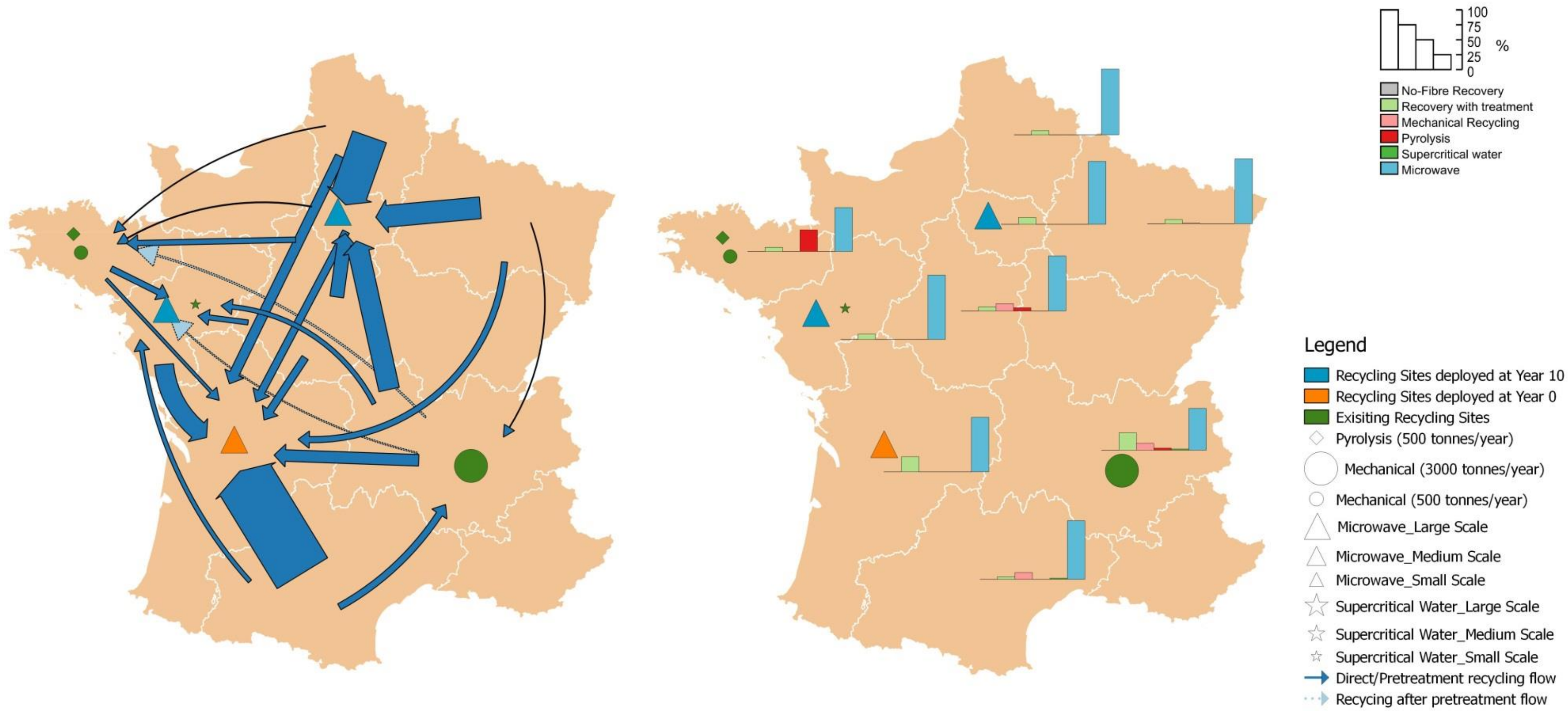


Figure 5-14: Snapshot of configuration for Strong Increase-3T (M-TOPSIS point of 2€/kg of fibre) of the whole horizon time: right. Waste flows; left. Waste allocation on waste treatment techniques

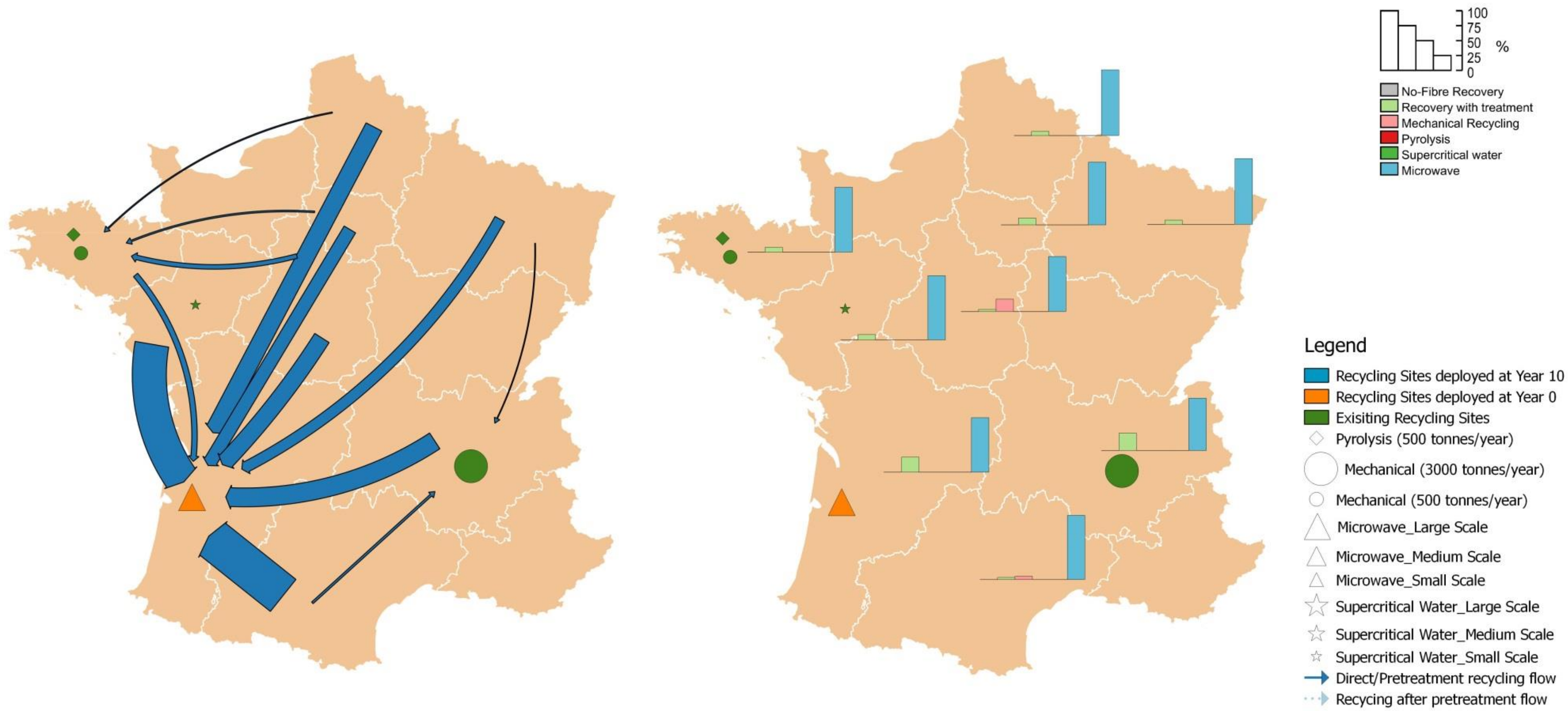


Figure 5-15: Snapshot of configuration for Light Increase-4T (M-TOPSIS point of 3 €/kg of fibre) of the whole horizon time: right. Waste flows; left. Waste allocation on waste treatment techniques

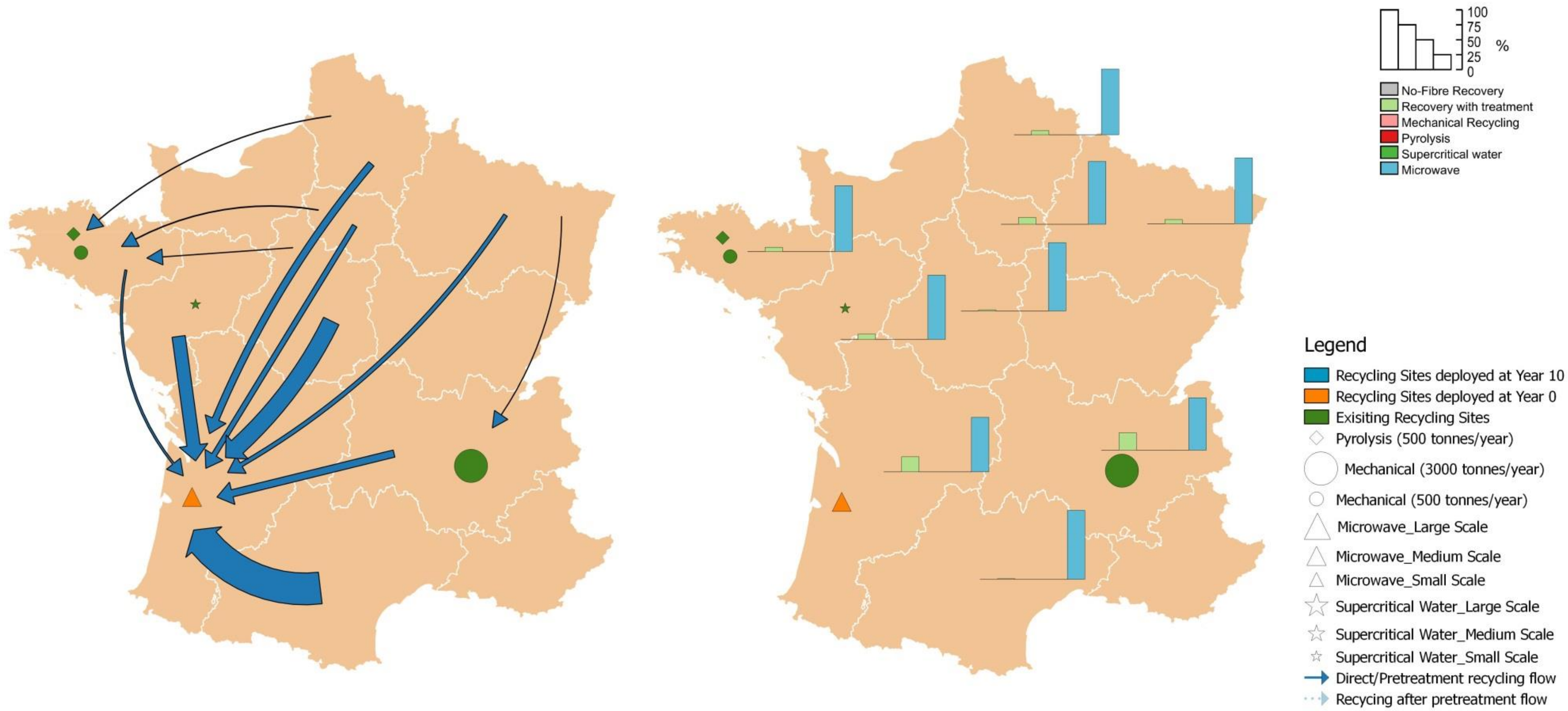


Figure 5-16: Snapshot of configuration for Light Decrease-4T (M-TOPSIS point of 3 €/kg of fibre) of the whole horizon time: right. Waste flows; left. Waste allocation on waste treatment techniques

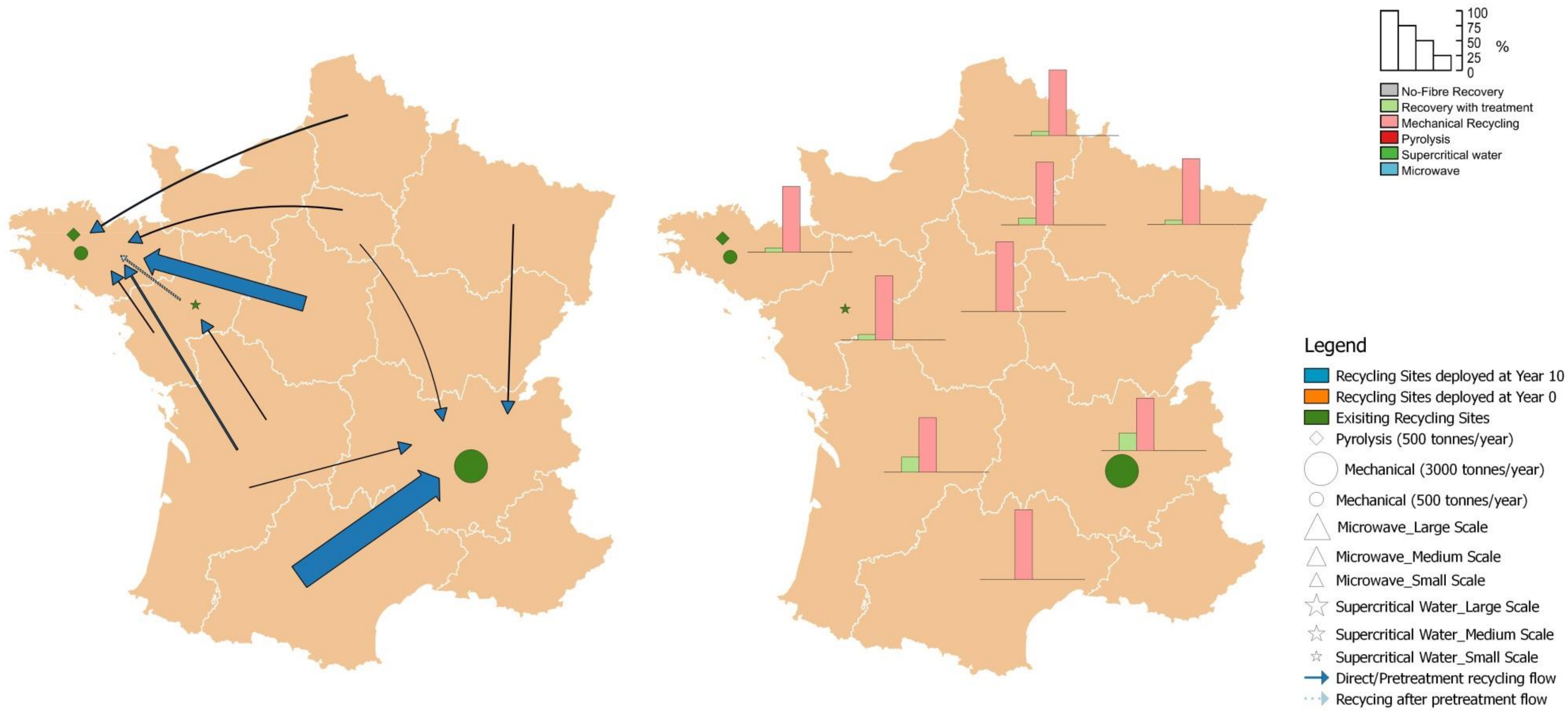


Figure 5-17: Snapshot of configuration for Strong Decrease-2N (NPVmax point of 1 €/kg of fibre) of the whole horizon time: right. Waste flows; left. Waste allocation on waste treatment techniques

5.5. Conclusion

This chapter has presented a modelling framework for the deployment and design of aerospace CFRP waste supply chain taking into account a multi-period formulation and combining Mixed Integer Linear Programming formulation, ε-constraint, lexicographic techniques and MCDM tools.

The methodology has been applied to a case study of France. The results have shown that the interpretation of the results is highly dependent from the scenario considered thus suggesting that the estimation of waste evolution is decisive for waste management system design.

The results also highlights that a mix of technologies will be involved in deployment phase and that the answer is not straightforward due to the complexity of the system. The methodology is yet generic enough to be used in different contexts and the advance in technologies could be taken into account in order to update the database concerning process data.

To conclude, some elements could be mentioned which may not be considered as "too" context-dependent:

- Decentralisation allows an important reduction of GWP but it is expensive strategy and inappropriate in the industrial context without high-value applications for recovered fibre. The compromise strategy for both economic and environmental objectives are centralisation at the regions which are close the important waste sources. The cooperation in the recovery system is needed to minimise cost and maximise profit. The multi-criteria tools in GIS can help to determine the location more precisely than this study which is based on average distance between regions and without the actual distances between waste sources in the same region.
- The bi-criteria optimisation with economic criterion (Cost minimisation or NPV maximisation) and environmental criterion (GWP minimisation) confirms the conflicts between these objectives. But if the recovered fibre is evaluated at appropriate value for its utilisation, these objectives can be improved together. In this study and probably in the current context of CFRP treatment process, microwave appears to be a promising process treatment for the recovery system because of its moderate investment, high yield of recovered products with low cost of treatment.

CHAPTER 6

Conclusions and Perspectives

6.1. Conclusions

The technical innovations have spread the utilisation of composite materials in numerous applications from aerospace to sports. Due to the increase of fossil fuel price, composite materials have substituted progressively the conventional metallic materials for mass savings in aerospace sector. The advantages of these materials are their high strength, low density and excellent corrosion resistance which allow reducing airplane mass and maintenance time. The recent jet airliners models (B787, A350) have more than 50 wt% on composites with the important primary and secondary structures such as fuselage, wings, rudder on Carbon Fibre Reinforced Polymer (CFRP) composite.

In contrast to the rhythm of their utilisation, waste management of composite materials has progressed slowly. Landfill and incineration are still the most used solutions for CFRP wastes due to economic concern and the durability of this material. Yet, the production of carbon fibre and CFRP is very energetic and requires high investment, especially for aerospace use. Recycling can be a relevant solution in waste management for environmental and economic benefit in order to reduce waste disposal and get material recovery for the high demand of carbon fibre.

In this context, there are more and more studies and initiatives of industries and academics, principally in recycling techniques and aircraft dismantling. Various technologies of carbon fibre recovery from CFRP waste have been developed in different scales from laboratory to industry from the three main types, i.e. mechanical recycling, thermal recycling and chemical recycling. Besides the pressure from the regulations of disposal restriction, the industrialisation of recycling depends on the balance between the quality of recyclates and treatment conditions (cost, emissions) which will position CFRP recycling options with disposal routes and markets of composites.

Actually, recycled carbon fibres are mainly used to substitute the virgin glass fibre in low cost composites like SMC and BMC due to the degradation of their mechanical properties from recycling process. The advancement on recycling techniques and on conditioning of recycled fibres has improved this problem for mechanical applications while recycled carbon fibres can be reused in a large range of products which do not require high mechanical properties, such as heat insulator, anti-electrostatics, etc. Due to the long life span of aircraft, cutting production wastes are the current dominant streams while end-of-life waste will become important in 20-30 years with the retirement of high CFRP-content airplanes.

The scientific objective of this thesis was to model the whole CFRP waste supply chain and to consider the different objectives that are involved in the design problem, e.g. minimisation of cost and environmental impact. The scientific aim was to develop a generic framework that can take into account the design of the CFRP waste supply chain considering a national scale with many CFRP waste sources of the aerospace industry and that can embed the various treatment technologies. More practically, an optimisation framework that allows the generation of quantitative information when all the nodes of the system are defined and integrated was developed. Particular emphasis was devoted to address the multi-objective formulation in which economic and environmental criteria must be simultaneously taken into account at the earlier design stage.

Achievements from a methodological viewpoint:

A methodological framework that was implemented in successive steps was developed to achieve these goals:

- An exhaustive review of CFRP/FRP recovery options was the core of Chapter 1. This step was mandatory to have a precise idea of the characteristics of the system and to collect data for modelling and optimisation, i.e. the nature of materials/wastes, the available waste treatment techniques, the general modelling framework of waste management

- Chapter 2 was dedicated to the methods and tools that constitute the elementary bricks of the methodological framework.

- The collected data have then been consolidated and analysed through economic and environmental assessment of the different technical pathways. Different waste treatment techniques from the Non-fibre recovery routes, i.e. landfill, incineration and co-incineration to the Fibre recovery pathways, i.e. grinding, pyrolysis, microwave, and supercritical water, have been studied as the elementary echelons of the supply chain system. Moreover, various economic and environmental indicators are used to represent different viewpoints of the involved stakeholders in the CFRP waste treatment supply chain. The effects of maturity level, plant scale, and carbon fibre recovery rate in different markets are also discussed in Chapter 3.

- Chapters 4 and 5 are dedicated to the modelling and optimisation of the whole system for aerospace CFRP waste management.

The system is modelled through a three-echelon supply chain, i.e. “waste-treatment-products”. The model consists of different waste types from multiple sources at input, multiple treatment techniques which release multiple recovered products at different quality and recovery rates, and multiple markets. The compatibility between wastes and treatment options is considered in the model by allocation rules.

A bi-criteria optimisation approach based on a hybrid method combining lexicographic and ε-constraint techniques was implemented taking into account economic and environmental objectives. The models are developed on GAMS 24.4 interface and optimised by CPLEX 12. The final compromise solution is then selected from a range of optimal solutions obtained by the successive use of lexicographic, ε-constraint methods with Multi-criteria Decision Making methods.

Problem formulation is based on mathematical programming that constitutes a consistent way to model the typical items of the supply chain and their interconnection in a multi-objective approach considering both economic and environmental criteria. The problem corresponds to a location routing type to design at a strategic level, the aerospace CFRP waste management using deterministic data in mono/multi-period formulations for the short and long term scenarios. The problem is referred to Linear Programming (LP) (Chapter 4) or Mixed Integer Linear Programming (MILP) for a mono-period or a multi-period approach respectively.

The selection of a compromise solution from the Pareto front is determined by the use of Multi-criteria Decision Making (MCDM) tools. For a mono-period vision, the M-TOPSIS method was robust enough to discriminate the solutions. The basic principle of this method is to find the best alternative by simultaneously minimising the distance to the positive ideal solution and maximising the distance to the negative ideal solution.

For the multi-period approach, the evolution of waste quantity related to aerospace industry over a 20-year horizon time is considered. Different waste scenarios are modelled to study the impacts of the different trends on evolution of waste quantity. A strategy of optimisation is proposed to assess the economic profitability for recyclers and the potential insertion of recycled fibre into different markets. Two bi-criteria optimisations are carried out: i) minimisation of cost and minimisation of GWP impacts in order to determine the different ranges of price for recycled carbon fibres; ii) maximisation of Net Present Value (NPV) and minimisation of GWP impacts with a range of fixed prices recycled carbon fibre corresponding to different markets. In each waste scenario, the relevant solution of waste management system is selected by the successive use of two MCDM methods, i.e. M-TOPSIS and PROMETHEE-GAIA for three criteria: minimising recovered fibre price, maximising Net Present Value (NPV) and minimising GWP impacts.

The case study considered is based on the deployment of the aerospace CFRP waste supply chain but the methodology is generic enough to be extended to other scales.

Achievements from a process systems engineering viewpoint for CFRP waste management:

- Since a mix of treatment techniques is considered, each one with its own characteristics, i.e. operating conditions, treatment cost, and emissions, the configuration of the global waste management system embeds a wide range of choices concerning techniques, wastes and locations.

- The choice of techniques reflects the conflicts of interest between economic and environmental criteria in waste management. Cost minimisation tends to the cheapest options but leading to low added-value recovered products, i.e. landfill and grinding. These solutions allow waste owners removing their wastes at the minimum cost, however, giving poor profit for recyclers. In contrast, minimisation of GWP impacts promotes the use of most advanced technologies, such as supercritical water for maximisation of recovery yield and value, as well as minimisation of GHG emissions.

- The four waste types considered in this study have specific characteristics in each recycling technique. The priority of recycling is followed by the difficulty of treatment: dry fibre, cured production, uncured production and end-of-life. As they can be recovered by shredding at whatever recycling plant, most of dry fibres in the system can be recycled if the recycling plants are not so far from waste sources so that non-fibre recovery routes on site are cheaper than recovery and transport costs. End-of-life waste requires the most resources for recycling that it is treated by the cheap treatment options like landfill or grinding if there is no appropriate recycling technique on site for economic objective. This kind of waste can be treated by microwave process at the minimum GWP impacts.

- Transport plays an important role in waste management. Indeed, recovery centralisation is suited for satisfying an economic objective to reduce the transport and investment costs. New recycling plants are erected near the important waste sources. Non recovery routes can have advantages over low-cost recycling techniques like grinding due to their availability on site despite their slightly higher cost. A decentralised system is generally proposed to reach minimum GWP impacts, in which all waste sources have their own recovery sites. In the compromise solution for bi-criteria optimisation, a centralised system is yet preferred as the GWP impacts and the cost from transport activity are respectively lower than those resulting from waste treatment process and investment cost.

- The compromise solution obtained from the Pareto front by application of MCDM methods for both economic (minimisation of cost or maximisation of NPV) and environmental (minimisation of GWP) criteria uses a combination of different techniques to take advantages of each pathway. The results highlight that the choice of a recycling technique must not be performed separately by the decision has to be made considering the system as a whole with a panel of available techniques and their interaction along the supply chain. The strengths and the weaknesses of each technique compared to each other can be better appreciated in that way.

- For case study considered in this work, the following results have been obtained, which are which based on data collection performed during this PhD work (of course the conclusions may change according to the data set used):

Co-incineration is good for GWP minimising objective among Non-recovery pathways but it is more expensive than landfill and incineration and the recovered value is lower than fibre recovery techniques. For the case study, this technique has not been selected in the system. It can be used only if its cost is reduced to be competitive with landfill and incineration or if the restriction of waste disposal is imposed.

Pyrolysis is more expensive than grinding, releases high GHG emission, and provides lower quantity of recovered products than microwave and supercritical water. It has been yet selected in the optimisation process due to its vicinity of waste deposit. This technique can be yet improved by the recovery of oligomers rather than total combustion of matrix in order to reduce GHG emissions and increase recovery yield. However, the improvement needs to be kept competitive with the other techniques.

Although supercritical water leads to the highest recovery yield and the highest quality of recycled fibre, this technique is hard to apply for economic objective because its operation requires important resources (energy, water) compared to other recycling techniques. To be economically competitive, this technique may be operated in “lighter” conditions even though quality of recycled fibre can be slightly decreased.

- The estimation of waste evolution is decisive for waste management long term planning. Due to high investment cost associated with deployment, the system will optimise the existing capacity and create new recycling sites only under the pressure of waste overflows considering an economic objective, either cost minimisation or maximisation Net Present Value. Besides, multi-period approach is important for Net Present Value assessment to determine an acceptable deployment time.

- For the modelling of waste treatment pathways, it is relevant to consolidate the results that have been obtained from the studies of a specific recovery pathway and to highlight the potential that can be obtained considering the synergies between all the links of the supply chain.

- The economic assessment of recycling pathways shows the high potential for insertion of recycled carbon fibre in a large range of markets, from substitution of recycled glass fibre to low-cost virgin carbon fibre. The reutilisation of recycled carbon fibres in these markets depends on recycling technologies, plant scale and recovery rate.

6.2. Perspectives

Finally, several perspectives could be suggested in order to improve the proposed framework, to extend the approaches used in aerospace CFRP waste management in particular and waste management in general:

- CFRP waste supply chain modelling has been performed under a deterministic environment. Some assumptions have made due to the lack of data. A systematic sensitivity study could be carried out through experimental design to analyse the impacts of each component in the system.

- In the model, different steps of waste management can be under-estimated, like the preparation of wastes before recycling process (sorting, metals/contaminants removing) which can play an important role in selecting which recovery routes are appropriate for different waste streams.

- Although the markets for recovered fibres are considered in different approaches in this study, such as the minimum quality requirement in each market, presence of potential markets, range of different fixed prices for recovered fibre, these approaches are quite qualitative for the system, above all as far as fibre quality is concerned. A more quantitative approach could be relevant to study the impacts of this down-stream part in the system. The reverse supply chain of aerospace CFRP wastes could thus be developed from the classic waste management system.

- Regarding the production of aerospace CFRP wastes, the spatial boundary of this waste management needs to be extended to European even to a global scale in order to establish efficient network for collection, treatment and reuse of CFRP wastes between raw materials producers, suppliers of composite components, aircraft manufacturers, aircraft owners and dismantlers in aerospace sectors. Besides, commercial aircraft Maintenance, Repair and Overhaul (MRO) sites should be integrated in the system because of their global development with the increase in air traffic. These sites can be play an important role in the life cycle of aerospace components in general and of CFRP in particular, i.e. waste collection and reuse of recovered products through the replacement of damaged parts.

- For the sake of interpretation, the selected criteria in optimisation process do not constitute a complete signature of sustainable development assessment. The proposed framework is yet generic enough to insert other criteria when the assessment method and the corresponding data will be available. In addition to Global Warming Potential for GHG emissions, other global environmental impacts such as stratospheric ozone; resource depletion acidification and regional impact potential for acidification; eutrophication and toxicity or local impacts (water for instance) could be incorporated in the analysis from the works of ISM, Bordeaux. Concerning economic assessment, this work has only focused on microeconomic considerations. The issue of the impact of public recycling incentives within dynamic general equilibrium frameworks has been tackled by TBS in the SEARRCH project.

- This framework of aerospace waste management could be applied to wastes of other composites or other sectors, CFRP automotive for example.

- A rigorous treatment of uncertainty, going beyond the attempts we have seen so far in the literature, would be a very useful improvement for policy makers and private investors. This suggests that stochastic or dynamic programming methods could be useful to model the problem. Besides, GIS-based multi-criteria decision making could be applied to the selection of dismantling sites or recycling plants.

Finally, we hope to have contributed to give some answers to the complex design problem of the CFRP waste supply chain in which multiple processes, multiple criteria, multiple waste sources, multiple usage and multiple stakeholders must be taken into account to make this kind of recycling industry emerge.

Appendices

Appendix 1 – CFRP-content aircraft types delivered from 1991 to 2010

	Series (Source: Airliners.net, n.d.)	Delivery Period	Average operating Empty Weight (tonnes)	%wt Composite	%wt CFRP	CFRP weight (tonnes/airplane)
A300	A300B2-200; A300B4-200; A300-600, A300-600R; A300-600F	1974-2007	87.47	4.5 (Cinquin, 2002)	2.25* (50% of total composites)	1.77
A310	A310-200; A310-300	1983-1998	80.67	8 (Cinquin, 2002)	4* (50% of total composites)	2.90
A318	A318	2003-present	38.38	13* (A320 family-A318, A319, A320, A321)	9* (A320 family-A318, A319, A320, A321)	3.15
A319	A319	1996-present	39.88	13 (Liu, 2013)	9 (Liu, 2013)	3.23
A320	A320-200	1988-present	42.2	13* (A320 family-A318, A319, A320, A321)	9* (A320 family-A318, A319, A320, A321)	3.42
A321	A321-100; A321-200	1994-present	47.96	13* (A320 family-A318, A319, A320, A321)	9* (A320 family-A318, A319, A320, A321)	3.88
A330	A330-200; A330-300; Long range A330	1993-present	121.64	10.17 (Lopes, 2010)	9.172 (Lopes, 2010)	10.04
A340	A340-200; A340-300; A340-300 E; A340-500; A340-600	1993-2012	146.5	10.17* (A330-A340 family)	9.172* (A330-A340 family)	12.09
A380	A380-800	2007-present	277	25 (Airliner World, 2015)	22 (Airliner World, 2015)	54.85
MD-80	MD81; MD87; MD88	1980-1999	34.65	1 (Cinquin, 2002)	0.5* (50% of total composites)	0.16
MD-90	MD90	1995-2000	40.8	1 (Cinquin, 2002)	0.5* (50% of total composites)	0.18

MD-11	MD11; MD11F; MD11C; MD11CF	1990-2001	124.41	4.5 (Cinquin, 2002)	2.25* (50% of total composites)	2.52
B737 (Original & Classic)	B737-100; B737-200; B737-300; B737-400; B737-500	1967-2000	30.55	2 (NPTEL, 2016)	1* (50% of total composites)	0.27
B737 NG	B737-600; B737-700; B737-800; B737-900; BBJ; BBJ2	1997-present	41.25	8 (Liu, 2013)	6 (Liu, 2013)	2.23
B747	B747-100; B747-100SR; B747-200; B747-300; B747-400; B747SP	1969-present	170.44	1.75 (Cinquin, 2002)	0.875* (50% of total composites)	1.34
B757	B757-200; B757-300;	1982-2005	61.22	3 (NPTEL, 2016)	1.5* (50% of total composites)	0.83
B767	B767-200; B767-200ER; B767-300; B767-300ER; B767-400	1982-present	89.13	3.5 (Cinquin, 2002)	1.75* (50% of total composites)	1.40
B777	B777-200, B777-200ER; B777-300	1995-present	140.91	10 (Cinquin, 2002)	8.5* (85% of total composites)	10.78

*: assumption

Appendix 2 – Airbus & Boeing aircraft deliveries of each model from from 1991 to 2010 (pieces)

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
A300	25	22	22	23	17	14	6	13	8	8	11	9	8	12	9	9	6			
A310	19	24	22	2	2	2	2	1												
A318													9	10	9	8	17	13	6	2
A319						18	47	53	88	112	89	85	72	87	142	137	105	98	88	51
A320	119	111	71	48	34	38	58	80	101	101	119	116	119	101	121	164	194	209	221	297
A321				16	22	16	22	35	33	28	49	35	33	35	17	30	51	66	87	51
A330			1	9	30	10	14	23	44	43	35	42	31	47	56	62	68	72	76	87
A340			22	25	19	28	33	24	20	19	22	16	33	28	24	24	11	13	10	4
A380																	1	12	10	18
MD-80	140	84	43	23	18	12	16	8	26											
MD-90					13	25	26	34	13	5										
MD-11	31	42	36	17	18	15	12	12	8	4	2									
B707	14	5	0	1																
B717									12	32	49	20	12	12	13	5				
B737 (Original & Classic	215	218	152	121	89	76	132	116	42	2	0	0	0	0	0	0	0	0	0	0
B737 NG	0	0	0	0	0	0	3	166	278	280	299	223	173	202	212	302	330	290	372	376
B747	64	61	56	40	25	26	39	53	47	25	31	27	19	15	13	14	16	14	8	0
B757	80	99	71	69	43	42	46	54	67	45	45	29	14	11	2					
B767	62	63	51	41	37	43	42	47	44	44	40	35	24	9	10	12	12	10	13	12
B777					13	32	59	74	83	55	61	47	39	36	40	65	83	61	88	74
Total	769	729	547	435	380	397	557	793	914	803	852	684	586	605	668	832	894	858	979	972
Average wt% CFRP per plane	1.18	1.26	1.77	2.10	2.91	3.17	3.34	3.47	4.04	4.26	4.19	4.46	4.87	5.1	5.04	5.3	5.44	6.26	6.27	6.89

Appendix 3 – Inventories of waste production plants (sites)

Plant type	Scale	Regions											
		NPCP	NOR	BRE	ACAL	IDF	PL	CVL	BFC	ALPC	ARA	LRMP	PACA
Finished CFRP production	Small	0	0	0	0	1	0	0	0	1	1	1	0
	Medium	1	0	1	0	2	2	1	0	4	3	3	0
	Large	1	0	0	1	0	2	0	0	1	0	0	0
Prepreg Production	Small	0	0	0	0	0	0	1	0	0	0	0	0
	Medium	0	0	0	0	1	1	0	0	0	1	0	0
	Large	0	0	0	0	0	0	0	0	0	0	0	0
Carbon fibre Production	Small	0	0	0	0	0	0	0	0	0	2	0	0
	Medium	0	0	0	0	0	0	0	0	1	0	0	0
	Large	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 4 – Quality of recovered products from Fibre-recovery pathways and the quality requirement of markets

Waste type	Recovered product	Replaced material	Quality of recovered product (%)					Market 1 (NPCP, BRE, ACAL, IDF, PL, CVL, ALPC, ARA, LRMP)	Market 2 (NPCP, NOR, BRE, ACAL, IDF, BFC, ALPC, ARA)	Market 3 (All regions)	Market 4 (All regions)
			Shredding (Pretreatment)	Grinding	Pyrolysis	SCW	Microwave	Min. quality (%)	Min. quality (%)	Min. quality (%)	Min. quality (%)
Dry fibre	Fibre	Carbon fibre	100	x	x	x	x	90	80	x	x
CFRP waste (EOL, uncured and cured production)	Powder	Limestone	x	100	x	x	x	x	x	100	x
	Fibrous	Glass fibre	x	100	x	x	x	x	x	100	x
	Fibre	Carbon fibre	x	x	89	93	80	90	80	x	x
	Oligomers	Phenol	x	x	x	100	100	x	x	x	100

Appendix 5 – Distance between regions for road transportation (km)

	NPCP	NOR	BRE	ACAL	IDF	PL	CVL	BFC	ALPC	ARA	LRMP	PACA
NPCP	0	256	569	554	225	600	348	502	800	691	895	1001
NOR	256	0	311	638	142	387	241	444	655	594	787	904
BRE	569	311	0	830	349	107	302	617	461	738	700	1046
ACAL	554	638	830	0	490	865	587	330	970	493	972	800
IDF	225	142	349	490	0	384	130	313	582	464	678	773
PL	600	387	107	865	384	0	334	638	347	685	586	986
CVL	348	241	302	587	130	334	0	315	469	465	555	758
BFC	502	444	617	330	313	638	315	0	724	194	727	504
ALPC	800	655	461	970	582	347	469	724	0	556	246	645
ARA	691	594	738	493	464	685	465	194	556	0	537	314
LRMP	895	787	700	972	678	586	555	727	246	537	0	403
PACA	1001	904	1046	800	773	986	758	504	645	314	403	0

Appendix 6 – M-TOPSIS Method (Ren et al., 2007)

The successive steps of M-TOPSIS are detailed following:

Step 1: Establish the decision matrix with ***n*** alternatives evaluated by ***m*** criteria after tendency treatment.

		Criteria					
Alternatives		c_1	c_2	…	c_j	…	c_m
	x_1						
	x_2						
	…						
	x_i				X'_{ij}		
	…						
	x_n						

Figure A6-1: Decision matrix

Step 2: Build the normalised decision matrix ***A***

		Criteria					
Alternatives		c_1	c_2	…	c_j	…	c_m
	x_1						
	x_2						
	…						
	x_i				a_{ij}		
	…						
	x_n						

Figure A6-2: Normalised decision matrix A

With $a_{ij} = \dfrac{X'_{ij}}{\sqrt{\sum_{i=1}^{n} (X'_{ij})^2}}$; $i = 1, 2, ..., n$; $j = 1, 2, ..., m$;

***Step 3*:** Determine the positive ideal and negative ideal solution from the matrix A

$$A^{+} = \left(a_{i1}^{+}, a_{i2}^{+}, ..., a_{im}^{+}\right), a_{ij}^{+} = \max_{1 \le i \le n}(a_{ij}), \qquad j = 1, 2, ..., m$$

$$A^{-} = \left(a_{i1}^{-}, a_{i2}^{-}, ..., a_{im}^{-}\right), a_{ij}^{-} = \min_{1 \le i \le n}(a_{ij}), \qquad j = 1, 2, ..., m$$

***Step 4*: Calculate the separation measures using the n-dimensional Euclidean distance of each alternative from the positive ideal solution:

$$D_i^{+} = \sqrt{\sum_{j=1}^{m} (a_{ij}^{+} - a_{ij})^2 \times w_j}$$

from the negative ideal solution:

$$D_i^{-} = \sqrt{\sum_{j=1}^{m} (a_{ij}^{-} - a_{ij})^2 \times w_j}$$

with w_j : the weight of criteria ***j***

Step 5**:* Establish the $D^{+}D^{-}$ plane with the point (D_i^{+}, D_i^{-}) represents each alternative ***i; the point ***A*** $\left(\min\left(D_i^{+}\right), \max\left(D_i^{-}\right)\right)$ as the 'optimised ideal reference point'. Calculate the distance from each alternative to point ***A***

$$R_i = \sqrt{\left[D_i^{+} - \min\left(D_i^{+}\right)\right]^2 + \left[D_i^{-} - \max\left(D_i^{-}\right)\right]^2} \qquad i = 1, 2, ..., n$$

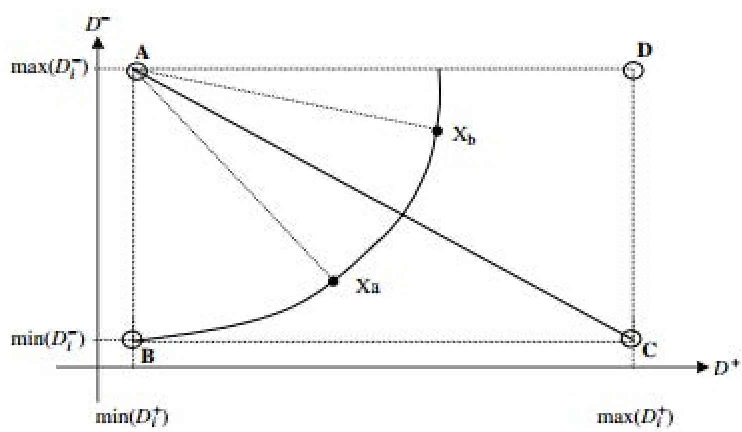


Figure A6-3: The idea of M-TOPSIS method (Ren et al., 2007)

Step 6: Rank the preference order on using the value of R_i. If there are two alternatives x_a and x_b with $R_a = R_b \ (a \neq b)$, calculate R_i by the formula following and choose the better one with the smaller R_i value:

$$R_i = D_i^+ - \min\left(D_i^+\right) \ i = a, b$$

Appendix 7 – PROMETHEE Method (Macharis et al., 1998)

The methodology of PROMETHEE is summarised in Figure A7-4 while each step is detailed hereafter.

I. Preliminary stage:

Successive steps are proposed to start the procedure and to reach a good basic structuring of the decision problem. If the problem is sufficiently structured in which alternatives and criteria are well defined from the beginning, this stage can be ignored and the evaluation process can start immediately.

Step 1: Collection of the opinions of the decision makers, the experts

According to the characteristics of the decision problem, the facilitator can meet the decision-makers and the experts either together or individually. Each decision-maker is encouraged to express his own opinions in order to progressively enrich the maturity of the facilitator with respect to the decision process.

Step 2: Description of the problem

The facilitator comments the available infrastructure and gives an overall description of the problem according to the information he has collected during Step 1.

Step 3: Alternative generation

All the decision-makers propose their alternatives with a description for each alternative. The nature of the alternatives depends on the nature of the decision problem. An important number of alternatives can be generated and described in a limited period of time.

Step 4: Stable set of alternatives

When the time allocated for the alternative generation is over, the facilitator will collect the proposals of alternatives from decision makers which can be displayed one by one to the audience. This step is an "open-discussion" phase. Each decision-maker discovers the proposals introduced by other colleagues and gives the comments to these proposals. A global view of the proposed solutions is given and a stable set of alternatives is defined on combining possible proposals, considering new ones, or eliminating the non-realistic ones. Additional alternatives can be added on by cycling back to Step 3.

Step 5: Comments on the alternatives

All the alternatives obtained at the end of the previous step are evaluated by the decision-makers in parallel.

Step 6: Evaluation criteria

This step is essential to select the relevant solution because each decision-maker is facing individual conflicts from the multicriteria nature of the problem on one hand, and on the other hand there are conflicts between decision-makers themselves. Common and individual criteria can be considered. The common criteria must be agreed by all the decision-makers while individual criteria can be considered by one or several decision-makers and not necessarily by the whole group. Then the criteria for which objective data exist can be evaluated.

The evaluation table of each decision-maker including n alternatives and k evaluation criteria is established at the end of this step.

Numerical evaluations are required in PROMETHEE method that qualitative scales, (e.g. very good, good, average, bad, very bad), will have to be transformed into numerical ones, such as 5, 4, 3, 2, 1.

<u>II. Individual evaluation stage</u>

The proposed alternatives are evaluated by each decision-maker with PROMETHEE methodology.

Step *7*: Weights of the criteria

The importance of each criterion for each decision maker is transformed to normed weight.

For a decision-maker $DM_r\,(r=\{1,2,\ldots,R\})$ in ***R*** decision-makers of the whole group, the weights associated to the ***k*** criteria are expressed:

$$\mathrm{w}_1^\mathrm{r},\ \mathrm{w}_2^\mathrm{r},\ \ldots,\ \mathrm{w}_\mathrm{j}^\mathrm{r},\ \ldots,\ \mathrm{w}_\mathrm{k}^\mathrm{r}$$
$$\sum_{\mathrm{j=1}}^{\mathrm{k}} \mathrm{w}_\mathrm{j}^\mathrm{r}=1$$

Step 8: Preference functions

According to the PROMETHEE procedure, a preference function must be associated to each criterion for pairwise comparisons.

For example: For pairwise comparison of alternatives ***a*** and ***b***

$$P_j(a,b)=G_j\left[f_j(a)-f_j(b)\right]$$
$$0\le P_j(a,b)\le 1$$

P_j is the preference function associated to criterion f_j , G_j is a non-decreasing function of the deviation between $f_j(a)$ and $f_j(b)$. If f_j is a criterion to be maximised, we will have

$$
\begin{cases}
G_j\left[f_j(a)-f_j(b)\right]=0 & \text{if} \quad f_j(a)<f_j(b) & \text{no preference} \\
G_j\left[f_j(a)-f_j(b)\right]\sim 0 & \text{if} \quad f_j(a)>f_j(b) & \text{weak preference} \\
G_j\left[f_j(a)-f_j(b)\right]\sim 1 & \text{if} \quad f_j(a)>>f_j(b) & \text{strong preference} \\
G_j\left[f_j(a)-f_j(b)\right]=1 & \text{if} \quad f_j(a)>>>f_j(b) & \text{strict preference}
\end{cases}
$$

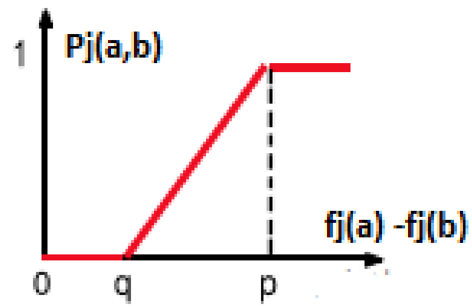
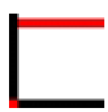
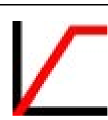
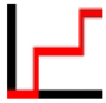


Figure A7-1: Linear preference function (q: indifference threshold; p: preference threshold)

The preference functions allow translating the deviations observed on a specific criterion into degrees of preference. Six basic types of preference functions are proposed in PROMETHEE in order to facilitate the selection of an appropriate preference function for each criterion. In each case, the preference function depends maximum on two parameters: indifference and/or preference thresholds.

Table A7-1: Six basic preference functions in PROMETHEE

Type	Form	Usage
Usual preference function		- No consideration of any threshold - Suitable for qualitative criteria, a criterion with a few very different evaluations
U-shape preference function		- An indifference threshold is required
V-shape preference function		- Indifference threshold is equal to 0 - Suited to quantitative criteria when even small deviations should be accounted for

Level preference function		- Suited to qualitative criteria when the decision-maker modulate the preference degree according to the deviation between evaluation levels
Linear preference function		- Best choice for quantitative criteria when an indifference threshold is wished
Gaussian preference function		- An alternative to the Linear preference function. - Difficult to set up due to a single Gaussian threshold between the indifference and preference thresholds - Less obvious interpretation and seldom used

All the preference functions of the common criteria will be the same for all decision-makers although the associated weights can be different.

***Step 9**:* Individual PROMETHEE-GAIA analysis

For each alternative ***a*** in the set A of alternatives, $\phi^{+r}(a)$ and $\phi^{-r}(a)$ respectively measure the power and the weakness of ***a*** with regard to the other alternatives. $\phi^{r}(a)$ is the net flow of alternative ***a*** for each decision-maker r (DM_r).

$$\begin{cases} \pi^r(a,b) = \sum_{j=1}^{k} P_j(a,b) \times w_j^r \\ \phi^{+r}(a) = \sum_{x \in A} \pi^r(a,x) \\ \phi^{-r}(a) = \sum_{x \in A} \pi^r(x,a) \\ \phi^r(a) = \phi^{+r}(a) - \phi^{-r}(a) \end{cases}$$

Each decision-maker has access to the three main PROMETHEE-GAIA tools: PROMETHEE I partial ranking, PROMETHEE II complete ranking, and GAIA plane. The PROMETHEE I partial ranking allows incomparabilities: one alternative is good on a subset of criteria on which another one is weak and vice versa. PROMETHEE II provides a complete ranking of the alternatives from the best to the worst ones. The GAIA plane displays graphically the relative positive of the alternatives with regard to the criteria and the conflicts between the criteria. Additional tools, such as walking weights and the decision stick/axe, are also available to the decision-makers.

Although the set of alternatives and the set of criteria are identical for all decision-makers, the evaluation can be quite different according to the individual weight distributions which depend strongly on the specific interests of each decision-maker. The values of the ϕ^r summarise the rankings of each decision-maker.

III. Group evaluation stage

This stage focuses on group decision support in order to take into account the specific viewpoints of the different decision-makers.

Step 10: Global evaluation matrix

Global evaluation matrix is established on combining the individual net flows of each decision-maker obtained in the preceding step with the weights (ω_r) fixing the relative power of each decision-maker in the group.

$$\omega_1,\ \omega_2,\ \ldots,\ \omega_r,\ \ldots,\ \omega_R$$

$$\sum_{r=1}^{R} \omega_r = 1$$

Step 11: Global evaluation

For a particular alternative, the global net flow for the whole group is the weighted sum of the individual net flows:

$$\Phi^G(a_i) = \sum_{r=1}^{R} \phi^r(a_i) \times \omega_r$$

At the end of Step 11, a global evaluation is obtained for the group. PROMETHEE II proposes a best compromise and the conflicts between the decision-makers are displayed in the GAIA plane.

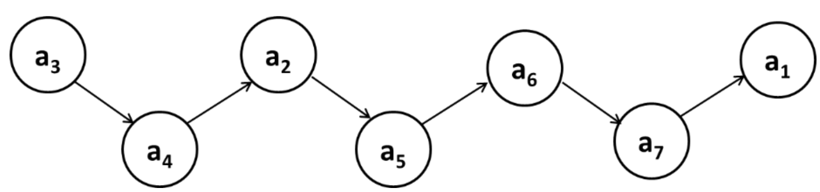


Figure A7-2: Global PROMETHEE II ranking

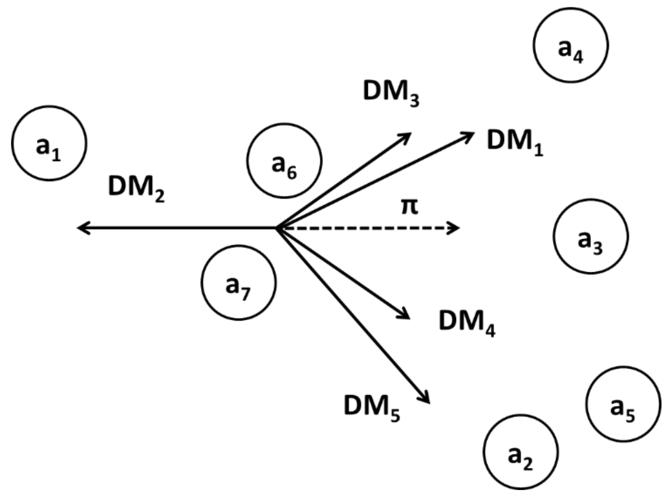


Figure A7-3:Positions of alternatives in Global GAIA plane

If the group agrees upon the results of the global analysis, the best compromise can be adopted. Otherwise, if there is no common agreement, the PROMETHEE procedure can remain and cycling back to Steps 1, 3, 6 , 9, 11 should be considered to reduce the conflicts and to find a compromise.

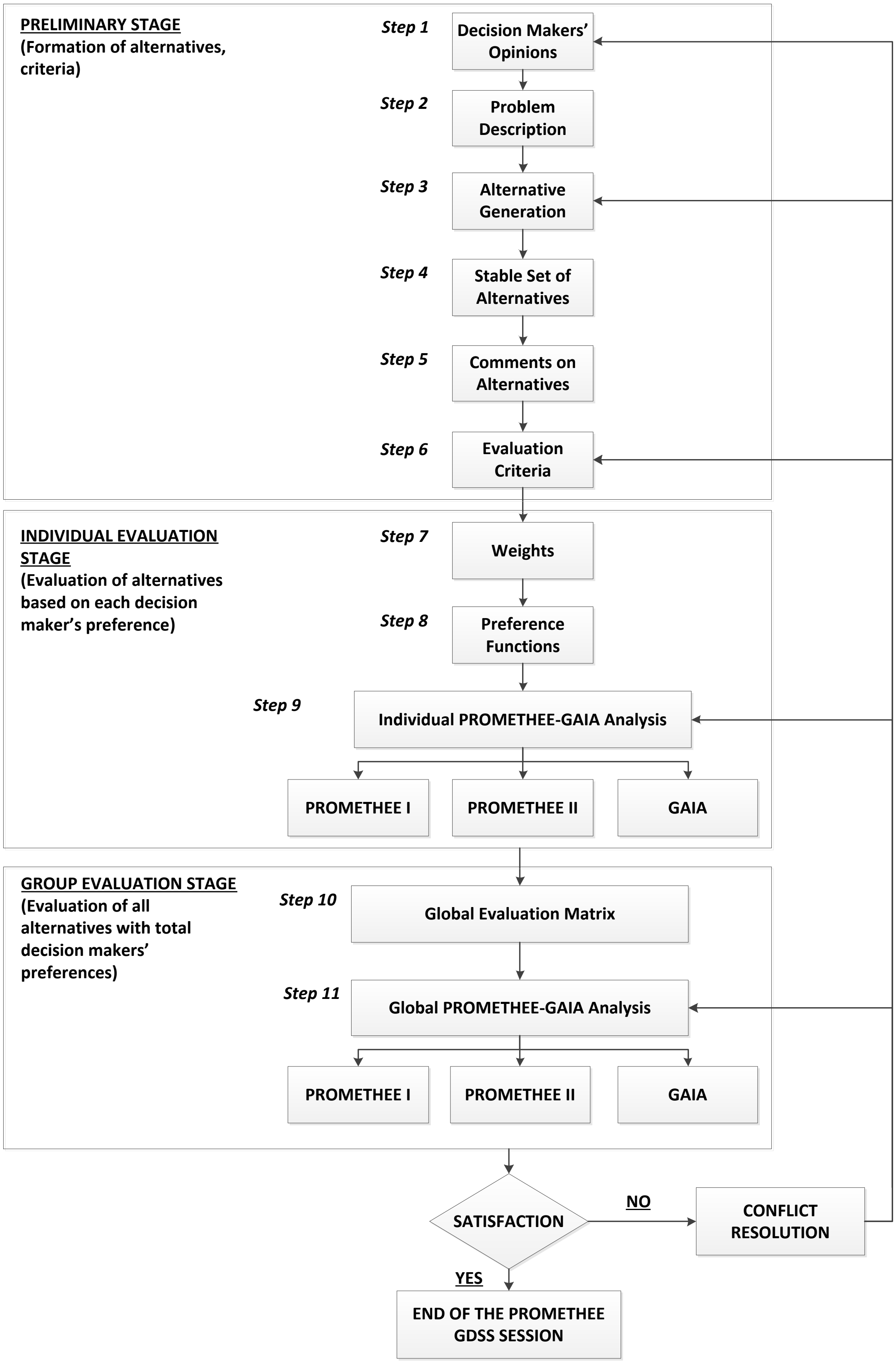


Figure A7-4: PROMETHEE methodology

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